Developing the silviculture of Continuous Cover Forestry: using the data and experience collected from the Glentress Trial Area

By

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Declaration

I hereby declare that this thesis is my own composition and has not been submitted for any other degree or qualification. The work described is my own except where stated otherwise. The lead author of Appendix A is Gary Kerr.

Hamish Mackintosh, June 2012

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Abstract

Continuous Cover Forestry (CCF) has become increasingly popular since the early 1990s. CCF utilises several silvicultural techniques in order to promote and enhance forest structural diversity and favours natural regeneration. As CCF is relatively new to the UK there are still areas of knowledge regarding management interventions that need to be improved upon. This study utilises simple models, seedling physiology and a hybrid gap model and applies them to the Glentress Trial Area which has been under transformation from even-aged forestry since 1952. These efforts have led to an improved understanding of thinning interventions and the effects they may have on future stand structure.

Since the formation of the Forestry Commission in 1919, clearfell-replant forestry has been the main form of management practiced in the UK. CCF management differs in several respects and is commonly practiced using expert knowledge in Continental Europe. In the UK the knowledge-base is still growing and therefore simple models can prove useful for guiding management. This study investigated the use of the idealised reverse-J and the Equilibrium Growing Stock (EGS). This study found that the reverse-J shaped diameter distribution is maintained at the Trial, Block and sub-Block scale indicating that an irregular structure is being approached. In addition, the diminution coefficient, a parameter of the reverse-J distribution, falls within values typical of continental Europe. Comparison of the actual diameter-frequency distribution against an ideal reverse-J distribution can inform both thinning intensity and which diameter classes to target.

The EGS, which is a volume–diameter distribution, examines standing volume and how that volume is distributed across three broad diameter classes. Typical distributions from the Swiss Jura indicate that percentage volume should be split 20:30:50 across diameter classes. The EGS analysis showed that standing volume in the Trial Area is much lower than European values at just 174 m^3 ha^{-1}. In addition, the classic 20:30:50 percent split was not observed. The 1990 data set showed a 49:43:8 distribution but by 2008 it was 40:41:19.

As natural regeneration is favoured in CCF a better understanding of seedling physiology is essential. This study established open (15-35 $m^2 ha^{-1}$) and closed canopy plots (>35 $m^2 ha^{-1}$). Plot characteristics were recorded and then seedlings were selected for physical measurements, chlorophyll fluorescence and gas-exchange measurements. There were clear differences between the physical characteristics with a mean Apical Dominance Ratio (APR) of 1.41 for the open plots and 0.9 for the closed plots which is consistent with previous studies suggesting an APR of 1 is needed for successful regeneration. The chlorophyll fluorescence measurements showed a linear relationship with PAR. However, although the results of the gas-exchange measurements showed an increase in photosynthetic rates with PAR for open plots, there was no obvious relationship in the closed plots. As a result, the study did not find a linear relationship between photosynthetic rate and chlorophyll fluorescence.

Finally a complex, hybrid gap model was used to investigate the effects of management on predicted future stand structure. The hybrid gap model, PICUS v1.41, was parameterised for Sitka spruce. The model was used to explore different management scenarios on stand structure over two time periods; 1954-2008 and 1952-2075. The output from the group selection with underplanting scenario, which resembled the actual management, produced realistic output that was comparable to the stand characteristics measured during the 2008 assessment. The output from the 1952-2075 runs suggested that thinning to a residual basal area suitable to allow natural regeneration (<30 $m^2 ha^{-1}$) or a group selection with underplanting were the best management options for maintaining structural diversity.

Contents

List of figures

List of Tables

List of Abbreviations and symbols

A	Photosynthetic rate (μmol CO2 m^2 s^{-1})
ADR	Apical Dominance Ratio
ANOVA	Analysis of Variance
BA	Basal Area (m^2)
BADC	British Atmospheric Data Centre
CCF	Continuous Cover Forestry
CCFG	Continuous Cover Forestry Group
DBH	Diameter at Breast Height (cm)
DSF	Direct Site factor
EGS	Equilibrium Growing Stock
ETR	Electron Transfer Rate (μmol m^{-2} s^{-1})
Fm	Maximum fluorescence from dark adapted leaves
Fm'	Maximum fluorescence under ambient light conditions
FMA	Forest Management Alternatives
GLM	Generalised Linear Model
GPP	Gross Primary Productivity
GPS	Global Positioning System
GSF	Global Site Factor
IRGA	Infra Red Gas Analyser
ISF	Indirect Site factor
m	Mortality proportion
NPP	Net Primary Productivity
OEC	Other Evergreen Conifers
PAM	Pulse-Amplitude-Modulation
PAR	Photosynthetically Active Radiation (μmol m^{-2} $s^{-1)}$
PICUS v1.4	A 3D hybrid gap model
PSII	Photosystem II
q	Diminution coefficient
RLC	Rapid Light response Curve
SLA	Specific Leaf Area (m^{-2} kg)

UNEP	United Nations Environmental Programme
USA	United States of America
Vissky	Proportion of sky visible through the canopy
VPD	Vapour Pressure Deficit (kPa)
WCC	Woodland Carbon Code
3-PG	The Physiological Principle in Prediction Growth model.

Contributions to chapters

Below are outlined the various contributions made to each chapter:

- Chapters one and six were the work of Hamish Mackintosh.
- Chapter 2: Hamish Mackintosh carried out the field work, wrote the text and produced the figures. Gary Kerr gave valuable feedback and advice on draft versions of the text. Thomas Connolly gave valuable initial advice on statistical analysis and prior to the chapter being submitted to Scottish Forestry checked that the statistical analysis was of an acceptable standard.
- Chapter 3: Hamish Mackintosh carried out the field work, wrote the text and produced the figures. Gary Kerr gave valuable feedback on draft versions of the text. Thomas Connolly gave valuable initial advice on statistical analysis and prior to the chapter being submitted to Scottish Forestry checked that the statistical analysis was of an acceptable standard.
- Chapter 4: Hamish Mackintosh carried out the field work, wrote the text and produced the figures. Mike Perks and Maurizio Mencuccini both provided valuable advice when planning the field work and gave good feedback and comments on early versions of the chapter.
- Chapter 5: Hamish Mackintosh carried out the field work, wrote the text and produced the figures. Werner Rammer and Georgrios Xenakis provided essential information on the workings of the model and helped to write the scripts necessary for running the scenarios. Mike Perks and Maurizio Mencuccini provided useful feedback on drafts of the chapter.

Chapter 1

An Overview of Continuous Cover Forestry

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1.1 What is Continuous Cover Forestry?

Continuous Cover Forestry (CCF) is an approach to forest management that utilises several different silvicultural systems. Producing a CCF stand should never be a management goal in itself, instead decisions should be based on management objectives, site conditions and social factors (Mason and Kerr, 2004). There are many definitions of CCF but for the purpose of the thesis the Forestry Commission's (2011) where management aims to produce a continuous canopy with two or more distinct layers, favours natural regeneration and encourages species diversity. In this case, "continuous" is defined as lacking gaps bigger than a quarter of a hectare as fellings greater than this size are considered clearfells (Mason *et al.*, 1999).

1.2 Silvicultural systems associated with CCF

There are many different silvicultural systems that can be utilised within CCF. Matthews (1989) defines a silvicultural system as being "the process by which the crops constituting a forest are tended, removed, and replaced by new crops, resulting in the production of stands of a distinctive form". The most commonly used systems in the UK at present are:

Selection systems: These systems involve the removal of either single trees or small groups from throughout the forest (Matthews, 1989). When single trees are harvested only small gaps are created in the canopy and shade-bearing species are required. However, a group can also be selected, whereby a number of trees are removed to create a larger gap in the canopy. This adaptation is essential if intermediate or light demanding tree species form the stand. The implementation of a selection system follows a few guiding principles:

1. Natural regeneration should be thinned around wherever possible.
2. Trees competing with potential final crop trees should be removed.
3. The maintenance of a good size class structure should be borne in mind when carrying out any interventions. An example of a good

structure would be a reverse-J shaped diameter distribution (discussed in Chapter 2).

Shelterwood systems: These systems would not meet the strict definition of CCF used by some but meet the requirements outlined by the Forestry Commission (Mason *et al.*, 1999). Shelterwood systems are generally considered to protect regeneration and commonly use natural regeneration. The overstorey is usually felled in two to three successive fellings by which point the developing regeneration should be at an advanced stage (Matthews, 1989). There are many different types of shelterwood but those most pertinent to CCF are:

1. Uniform shelterwood system: Defined as being uniform both due to the uniform opening of the canopy and the creation of a regular regeneration layer (Hart, 1995). Over two to three successive canopy thinnings, the canopy is removed leaving a well developed under-storey. A seed tree system is a modification of this where a higher degree of the canopy is removed more quickly, typically leaving 10 to 25 m^2 ha^{-1} basal area. The purpose of the over-storey is to provide a seed source for natural regeneration, therefore when choosing trees to remain both seed production and wind firmness are a key consideration (Matthews, 1989).

2. Group shelterwood system: This system differs from a group selection system as when future thinning interventions are implemented the initial group is expanded allowing further regeneration at the edge of the initial group to develop. This continues until groups eventually join up with the oldest trees at the centre of the group and the youngest around the perimeter. The size of the groups should be at least twice the height of the surrounding canopy trees (Malcolm *et al.*, 2001). With this system, the initial group felling should be based around the existence of advanced regeneration beneath the canopy (Jeffrey, 1956; Matthews, 1989).

3. Irregular shelterwood system (Femelschlag): This system incorporates elements of the selection system and the group shelterwood system. The crop is tended and selected from an early age with the aim of producing high quality timber. The regeneration period is long and indefinite (typically over 50 years) and the groups that are felled are distributed unevenly through the forest creating a more heterogeneous structure (Matthews, 1989).

1.3 A brief history of CCF

The name CCF is derived from the German word "Dauerwald", first used by Alfred Möller in 1913 and is literally translated as "continuous forest". CCF is considered to have evolved from traditional selection systems which were employed throughout upland areas of central Europe (Pommerening and Murphy, 2004). Though selection systems have been used for hundreds of years in these regions, their current form arose between 1880 and 1920 and it was around this time that CCF gained recognition throughout Europe and the various silvicultural methods such as single tree selection, small group selection and irregular shelterwoods were defined (Matthews, 1989). The French forester Adolphe Gurnaud and his Swiss colleague Henry Biolley began to promote the transformation of even aged stands to selection forests, which make use of single tree selection or small group fellings, using the *Methóde du controle* (or Check method, described in Chapter 2) towards the end of the 19^{th} Century (Pommerening and Murphy, 2004). Karl Gayer's (1898) promotion of management based on natural processes was also influential. Following this De Liocourt (1898) noticed that within a selection forest the number of trees decreases with each increase in diameter class. When the diameter distribution is graphed, the line of best fit can commonly be described by a negative exponential equation. This was popularised by Meyer (1952) who derived an equilibrium diameter distribution that could be used as a silvicultural guide. This equilibrium diameter distribution is an assumed distribution where the stand can yield a constant volume without affecting stand structure (O'Hara, 2002). It seemed to reach its peak in popularity shortly after the publication of "Continuous Forest" (Möller, 1920) as cited in (Troup, 1927)) and Möller's use of the Barenthoren estate near Dessau as a demonstration site (Helliwell, 1997). Troup (1927) states that "few terms in European forestry have enjoyed more notoriety in recent years than that of Dauerwald". In the mid-twentieth century the popularity of CCF in much of Europe decreased due to Möller's death, attacks on its principles from critics such as Eilhard Wiedemann, and its compulsory uptake imposed by National Socialist Germany (Pommerening and Murphy, 2004).

The UK developed its clearfell-replant approach using exotic conifer species to create a strategic timber reserve in case of future conflict (Forestry Commission, 2012). However the UK does have some early examples of CCF including the use of uniform shelterwood systems in the Scottish lowlands as early as 1810 (Hart, 1995). Later, the Duke of Buccleuch at Bowhill (near Selkirk) made use of selection systems, CCF was practiced in the Forest of Dean from 1896 and a selection system was used by the Coke family at Weasenham wood in the early 1900s (Hart, 1995). Later, Professor Mark Anderson established several trial areas throughout Scotland investigating the transformation from clearfell-replant to CCF using group selection systems (Hart, 1995).

Though CCFs origins are European, it has also been widely adopted in the United States of America (USA) where it has undergone similar periods of popularity and disregard. Silvicultural systems associated with CCF reached the USA in the early 1900s (O'Hara, 2002). Selection systems were widely adopted but not implemented correctly. During the 1930s the depression had an impact on forest management decisions and as small diameter trees did not have a viable market this often resulted in economic selection cutting where the highest value, large trees were removed (Baker, 1950; O'Hara, 2002). This practice mainly occurred between 1930 and 1950, with old growth Douglas-fir stands in the Pacific northwest being the main example (Smith, 1986). As a result, after 1950, selection systems decreased in popularity as they had become associated with ignoring investment in regeneration and high-grading of the over-storey (Smith, 1986). Since 1970, the irregular systems used have been more akin to variations of the shelterwood system than selection systems (Smith, 1986). However, the USA, like Europe, has experienced a resurgence in the popularity of CCF during the early 1990s with northern hardwoods, southern pines and ponderosa pines all being managed using silvicultural systems associated with CCF (O'Hara, 2002).

CCFs current popularity can be traced back to the early 1990s when environmental concerns moved up the international agenda. In 1989 the group Pro Silva Europe was formed as an association of foresters who employed management influenced by natural processes (Schutz, 2007). In Britain, the Continuous Cover Forestry Group (CCFG) was formed not long after this in 1991 with the aim of increasing awareness and providing training in the low impact silvicultural systems associated with CCF. Only a year later, in 1992, the Statement on Forest Principles was signed and since then it has continued to gain momentum. These principles were then adapted to European forestry and formalised in the 1993 Helsinki guidelines. The Lisbon Declaration of 1998 further emphasised the social and cultural importance of forests (Warren, 2002). The UK Forestry Standard promotes the use of low impact methods such as CCF (Forestry Commission, 2004) and this is echoed in the Scottish Forestry Strategy which puts emphasis on the issue of sustainability (Scottish Executive, 2006). The National Assembly for Wales' policy is to adopt alternative management systems to clearfelling where they would make a better contribution to ecosystem services (Welsh Assembly Government, 2009).

It is likely the adoption of CCF will increase over the coming years. Mason *et al*. (2009) looked at the distribution of five different forest management alternatives (FMA) ranging in intensity from unmanaged forest nature reserve to wood biomass production. Two of these scenarios, close to nature forestry and combined objective forestry, include the use of CCF. The authors interpreted data from the report on the State of Europe's Forests (MCPFE, 2007) and found that in 2005 these two FMAs occupied 7 and 35 percent of forests in the UK respectively. However, as a result of current policy drivers Mason *et al.* (2009) estimated that by 2025 they could increase their share by 8% and 15% respectively.

1.4 Advantages and disadvantages of CCF

<u>1.41 Advantages</u>

There are various benefits associated with CCF relative to clearfell–replant which has been the standard form of forest management in the UK since World War One. The main perceived benefits relate to aesthetics (Ribe, 1989; Kohsaka and Flitner, 2004), enhanced biodiversity (Kerr, 1999; Bengtsson *et al.*, 2000; Michelsen, 2008) and resilience to climate change and pest species (Stokes and Kerr, 2009).

It seems intuitive that CCF has aesthetic benefits over clearfell-replant forestry. However, aesthetic value is subjective and varies with geographical area (due to associated culture) and between different groups of people e.g. gender differences. Research by Kohsaka and Flitner (2004) found that aesthetic perception varied between Germany and Japan. Japanese people viewed forests as commodities and therefore tended to favour images containing evidence of management or human presence. On the other hand, Germans associated forests with mystery and romance and hence favoured images appearing to be natural. In addition there is within nation variability. Despite this variability: spatial variety, multilayered canopies and mitigating the visual impact of harvesting are all generally associated with increased aesthetic value and are features of CCF (Ribe, 1989).

In an irregularly structured forest there are an increased number of niches to exploit and therefore biodiversity is thought to be enhanced through CCF management. However, species richness and biodiversity are terms often used interchangeably but the United Nations Environmental Programme (UNEP) states that biodiversity should include “diversity within species, between species and of ecosystems” (UNEP, 1992). The logistical problems of documenting every species, within species diversity and the diversity within the ecosystem for a given area are considerable. This has resulted in the use of key biodiversity indicator species that are easy to identify (Kerr, 1999). However, this method is extremely variable depending on the species group used. For instance, Lawton *et al.* (1998) found that on average only 10 to 11 % variation in species richness in one group is predicted by change in another group. Perhaps due to this, indirect indicators that focus on conditions known to be important to biodiversity are increasingly used. In the case of forests, this recognises the importance of structural diversity both at the stand and landscape level and the management and disturbance regimes that the forest experiences (Michelsen, 2008). In addition to this, it has been suggested that management that results in woodlands resembling "near natural" or old growth woodland have a higher level of diversity. This is in part due to the habitat produced by older, larger trees that provide deadwood habitat for many insect species and also due to their quasi-natural disturbance regime. The natural cycle of disturbance events allows natural ecosystem processes and vegetation dynamics to occur. It has been suggested that clearfelling is a way of recreating natural disturbance patterns. Despite the fact that there are superficial similarities, many of the ecological processes that occur on disturbed sites do not occur on clearfell sites (Bengtsson *et al.*, 2000).

Resilience to extreme weather events and pathogens is another benefit associated with CCF management. It is anticipated that with climate change there will be an increased risk associated with forest pathogens (La Porta *et al.*, 2008). As CCF commonly utilises a mixture of species it slows the spread of species-specific pathogens and ensures the entire stand is not affected (Nyland, 2003; Stokes and Kerr, 2009). Similarly, as CCF systems have at least one canopy layer with a developed understory they are more resilient in the face of storm damage such as wind throw which is predicted to increase as a result of climate change (Fuhrer *et al.*, 2006). This occurs as advanced regeneration beneath the canopy layer can take the place of the wind-thrown canopy, thereby ensuring a quicker and cheaper recovery.

1. 4. 2 Disadvantages

Despite the various benefits associated with CCF management, there are still several disadvantages and some contentious issues, relative to clearfell-replant management.

CCF is only suitable on sites that meet certain requirements. Windthrow risk is an issue when transforming an even-aged stand to CCF. Gardiner *et al.* (1997) found that the exact method of thinning was not important when considering resistance to windthrow. However, the size of any gaps or racks created within the stand was significant with the loading on exposed trees increasing quickly as gap size increases.

Furthermore, soil depth and drainage have an effect on rooting depth and therefore stability (Hale *et al.*, 2004). It is recommended that the forest stand wind risk model ForestGALES is used to assess suitability and if unavailable transformation should only commence in stands with a windthrow hazard class of one to three (Mason and Kerr, 2004).

Natural regeneration is a desirable element of CCF (Mason and Kerr, 2004). Below canopy light levels are of key importance to natural regeneration and are inextricably linked with thinning of the canopy. Hale (2003) found that there was a relationship between transmittance of light and basal area in Sitka spruce stands. Hale (2004) goes on to suggest critical basal areas for seedlings to achieve 50 percent of the growth achieved on an open site for several British conifer species with values ranging from 20 $m^2\ ha^{-1}$ in the case of larch to 40 $m^2\ ha^{-1}$ for western hemlock.

Browsing pressure is another site factor that has a large impact on the success of natural regeneration. Browsing can take the form of eating the actual seed in the case of squirrels and birds or browsing the seedlings themselves in the case of deer and rabbits (Mason and Kerr, 2004). However, deer tend to do the most damage. When deer exceed four to eight per km^2, either fencing or culling is essential, which in turn increases management costs. At levels below 4 deer per km^2 deer can promote regeneration as they create small bare patches suitable for regeneration and reduce vegetation competition (Warren, 2002).

The last site factor that needs consideration is soil quality. Soils of high fertility facilitate the colonisation of grass species, bramble and bracken which in turn hinder successful germination. Even if germination is successful, growth can be inhibited due to competition with these species. As a result relatively infertile soils are favourable when natural regeneration is desired (Malcolm *et al.*, 2001).

Perhaps the biggest disadvantage regarding CCF is that there is a lack of knowledge and experience of CCF amongst forest managers in the UK. CCF management in areas of continental Europe such as Slovenia and the Swiss Jura does not have this constraint as CCF has been widely used for long periods of time and forest managers have a good knowledge of how to implement a wide range of silvicultural systems (Helliwell, 1997; Pommerening and Murphy, 2004).

1.4.3 Contentious issues

A potential benefit of CCF is that the size range of marketable timber increases as trees are removed from a range of diameter classes during the same harvesting period. In general CCF results in a higher production of large diameter trees (Mason *et al.*, 1999). This is due to clearfell-replant systems seldom reaching the rotation lengths necessary to produce large diameter trees. Ensuring a premium price for timber with diameters over 60 cm is imperative to make CCF operations economically viable, but can be achieved if niche markets such as timber architects and builders are used (Mackintosh, 2008). However, this benefit is seen as a disadvantage by some as many softwood sawmillers classify logs of over 60 cm in diameter as outsized. This is due to softwood mills having adapted to utilise the output from traditional softwood plantations (Mason, 2007) .

The economics of CCF are still fairly contentious, with some suggesting that CCF management has a higher associated cost as management interventions involve numerous small scale operations and a high level of expertise (Hart, 1991) . However, as there have been few studies assessing the costs of CCF management, it is very hard to ascertain the exact costs involved (Mason *et al.*, 1999). Blyth and Malcolm (1988) looked at the costs incurred on the Glentress Trial Area over a seven year period. They found that establishment and maintenance costs were 10 to 50 % higher than the standard for that geographical area but that the harvesting costs did not differ significantly. However, care should be taken interpreting this information as it came from a trial area in the middle of its transformation period. The management was still in its early phases and tasks that take several man days at present may take significantly less time using experience gained from the trial. Davies and Kerr (2011) looked at the economic implications associated with carrying out clearfell-replant, transformation to a simple structure using natural regeneration, transformation to a simple structure using underplanting and transformation to a complex structure. Their results showed that net present value in perpetuity was higher for a simple CCF system than with clearfell-replant, providing that natural regeneration is successful.

Another contentious issue is whether there are timber quality benefits associated with CCF. A study by Macdonald *et al* (2009) used a literature review and timber properties model and found that transformation to CCF will not result in a significant change in timber quality but will produce a greater range of log properties and timber quality. The study noted that both the retention of trees to older ages and the use of crown thinning can improve timber quality but that gap creation in the canopy can have negative impacts.

As CCF retains some trees until much larger sizes than clearfell-replant management, there is potential for long term *in situ* carbon storage. Although mean annual increment decreases after a point in even-aged stands, the same may not be the case in complex CCF systems (Nyland, 2003; Poore and Kerr, 2009b). This is supported by Luyssaert *et al.* (2008) who found that boreal and temperate old growth forests have a net primary productivity (NPP) that is usually positive. Even in plantations it has been found that NPP does not always decline in the expected manner (Van Tuyl *et al.*, 2005). Indeed, it is often observed that younger stands, commonly associated with clearfell-replant, are sources of CO_2 as they involve extensive disturbance of the soil and humus layers which results in decomposition rates in excess of the NPP from stand growth (Kowalski *et al.*, 2004; Pregitzer and Euskirchen, 2004) whereas CCF involves less ground disturbance (Stokes and Kerr, 2009). Modelling studies investigating the effect of management on carbon sequestration under future climate change have found that there is more *in situ* carbon storage in stands managed under CCF than clearfell-replant (Thornley and Cannell, 2000; Seidl *et al.*, 2007; Seidl *et al.*, 2008). However, a study by Mason and Perks (2011) that looked at the carbon stocks of Sitka spruce managed using different silvicultural systems found that clearfell-replant systems had higher *in situ* carbon stored than CCF.

1.5 A brief history of the Glentress Trial Area

The Glentress Trial Area was established in 1952 by Professor Mark Anderson who was the head of the forestry department at the University of Edinburgh. Mark Anderson was interested in alternative silvicultural systems to the clearfell-replant forest management approach which predominated at the time. He was influenced by the fir-spruce-beech forests of the Swiss Jura which were managed using a single tree selection system (Wilson *et al.* 1999). This resulted in Prof Anderson establishing a number of long-term trial areas examining the transformation of CCF throughout

Scotland in areas such as Corrour, Faskally and Cawdor. One of these was located at Glentress, just east of Peebles in the Scottish borders.

The land on which Glentress forest now grows was purchased by the Forestry Commission in 1920, making it one of their earliest acquisitions (Anderson, 1955). In 1920 the majority of the area was rough pasture though there was some European larch and Douglas-fir planted on the upper slopes (Anderson, 1955). From 1921 through to 1949 planting took place with Douglas-fir being the preferred species at low elevations (240-320 metres), Japanese and European larch being planted on the mid slopes (320-400 metres) and Scots pine and Corsican pine planted in higher areas (400-560 metres) (Kerr *et al.* 2010b).

The Glentress Trial Area was established following an agreement between Professor Anderson and the Forestry Commission (Taylor, 1979). An area of 117 hectares was given to the University to produce management plans for which would then be enacted by the local Forest District staff. Professor Anderson's initial plan for the area was "to create and maintain in perpetuity a forest of irregular structure which will function primarily in a protective capacity". The method that Anderson chose to transform the forest from an even-aged to irregular structure involved the felling of small groups (Anderson, 1955). The Trial Area was split in to six areas (historically named Blocks) of approximately equal size. In any one year operations would take place within one of these Blocks. Each Block would then be returned to on a six year cycle. In the Block to be treated, a total of 2 hectares were felled across a series of small groups: generally 0.1 ha on the higher slopes and 0.2 ha at lower elevations (Wilson *et al.* 1999). During the early phase of the Trial Area these gaps were then planted at a very high density (> 10 000 ha^{-1}) though from the late 1960s these gaps were planted at lower densities (~2500 ha^{-1}) or left to regenerate naturally (Kerr *et al.,* 2010b). Anderson's (1955) aim was that over a 60 year period the entire Trial Area would have been felled and the regenerating groups would be at varying stages of development, thereby forming an irregular stand structure. Unfortunately, browsing pressure from both deer and sheep from neighbouring farmland combined with issues regarding management implementation has resulted in the 60 year transformation period being extended, with transformation estimated to be completed by 2033 (Blyth, 1993). The most recent management plan views transformation as an on-going process and has not set an end date for the “final” transformation to CCF across the Glentress Trial Area (Kerr *et al.,* 2010b).

In order to ascertain the progress of transformation, monitoring of the Trial Area has taken place. There have been three main monitoring periods in the Trial Area’s history. The first was from 1952 to 1964 when the check-method was employed which involved measuring the diameter of every tree on a periodic basis (Knuchel, 1953). At Glentress the diameters were measured in the Block that was due to be managed that year prior to any felling taking place. By comparing the diameter-frequency distributions at different points in time, progress of transformation could then be assessed. However, the check method is extremely labour intensive, estimated to take 10 hours per hectare (Malcolm, 1971). In 1964 the stand was still considered relatively even-aged. In addition to this there were staffing changes in the University meaning there was less labour available to conduct the monitoring assessments. Therefore the check-method was abandoned with the intention that it be resumed later in the transformation period (Taylor, 1979). This never occurred and subsequent monitoring in 1990 and 2008 was based around 240 permanent sample plots that were established in 1989 and 1990 (see section 2.2.2 for information of the plot assessments) (Kerr *et al*., 2010a).

1.6 Objectives and overview

Lack of knowledge regarding both the implementation of management and its costs and benefits relative to clearfell-replant management are two of the major issues that need to be addressed before CCF becomes more widely adopted in the UK. Until a firm evidence base is built up regarding the costs and benefits relative to clearfell-replant management systems are identified, many managers will be reluctant to implement the silvicultural systems associated with CCF. Furthermore, without knowledge regarding the best practice any management decisions that are made could result in a stand not reaching its potential in terms of stand structure, regerative capacity and timber quality. The primary aim of this thesis is to further our knowledge of the silvicultural systems associated with CCF.

In Chapter 2 the progress of transformation is assessed through the analysis of simple stand indices and a simple model; the ideal reverse-J distribution. The aim is to investigate the ability of the ideal reverse-J distribution to assess stand structure and inform the selection of stems for removal to move stand structure towards the “ideal” for CCF, and promoting natural regeneration. Chapter three further explores the use of simple models, this time utilising the Equilibrium Growing Stock (EGS) concept. It will be investigated in a similar way to the ideal reverse-J distribution in chapter two. These models are of great potential use as they could be used as an aide to management implementation. In particular, output from these models could help inform potential “ideal” stand structures, and through comparison with current stand structure, give valuable information on thinning intensity and what size classes of trees should be targeted. This in turn would address the issue of the current lack of knowledge of CCF management.

For CCF to be economically viable it is essential that natural regeneration is employed rather than planting (Davies & Kerr, 2011). In Chapter three the seedling physiology of Sitka spruce grown under continuous cover conditions is explored. This study investigated the differences in the architecture of seedlings grown under differing canopy conditions as well as seeking to characterise their photosynthetic physiology and its response to canopy cover and variable incident light levels. The objective of this work is therefore to further our understanding of the light requirements for Sitka spruce seedlings grown under CCF conditions, and provide insight into the optimal conditions for promoting understorey initiation and growth under existing canopy cover.

In chapter five a more complex hybrid gap model was parameterised for Sitka spruce and a number of management scenarios, each with a different silvicultural prescription, was investigated. The study aimed to establish the suitability of a hybrid patch model for representing the outcome of various interventions in upland, coniferous CCF. In addition to this the model outputs were interrogated to provide insight as to the capacity for such an approach to inform decision making through the prediction of future stand structure. This is particularly important in the UK as there are few established CCF stands, therefore modelling the effect of management interventions on stand structure may provide underpinning knowledge relating to the understorey response and development of varied stand structures.

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Chapter 2

Structural change and future management options for the Glentress Trial Area in Scotland

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Abstract

The Glentress Trial Area, established in 1952, is a long term experiment of the transformation of even-aged plantations to continuous cover management in upland, coniferous forests. This paper examines the structure of the Trial Area in 2008 and changes since 1990; it also examines the effects of different management scenarios, generated using a spreadsheet-based thinning guide, on the present structure. One of the main findings of the study is that the Trial Area is becoming increasingly dominated by Sitka spruce both in the canopy and in saplings and seedlings. The diameter distributions for each of the six Blocks of *circa* 20 ha continue to have a 'reverse-J' shape and this study confirms, for the first time, that they are also present at much smaller spatial scales. There has been only a small increase in basal area between 1990 and 2008 indicating that thinning and growth are in balance. However, overall there is a decrease in tree density indicating that individual tree basal area has increased. One reason for the reduction in density of trees is that in four of the six Blocks there is insufficient recruitment of saplings into trees to sustain the 'reverse-J' structures, which is a concern for the future of the Trial Area. Results from the effects of different management scenarios show that choice of the best 'target structure' must be made with reference to the management objectives of the stand and the stand dynamics of the species and site; some of the management scenarios led to the removal of all large trees, which are a key source of seed for regeneration and an important aesthetic asset.

2.1 Introduction

The longest running trial of the transformation of even-aged plantations to continuous cover forestry (CCF) is located at Glentress, Scotland (Kerr *et al*., 2010a). The Trial Area was established in 1952 by an informal agreement between Professor Mark Anderson, who was then the Head of the Forestry Department at the University of Edinburgh, and the Forestry Commission. The overall aim of the 117 ha Trial Area was to transform even-aged stands of conifers to an irregular structure using a group felling system over a 60-year transformation period. Other objectives were to create a forest with a composition and structure best suited to site conditions, optimize timber production, ensure a sustained yield and improve access by enhancing infrastructure (Anderson, 1955). A full account of the development of the Trial Area between 1952 and 1990 is given in Kerr *et al.* (2010a).

When Professor Anderson started the Trial Area, irregular silviculture was not widely practised in Britain. However, things began to change in 1989 with the formation of Pro Silva Europe, an association of foresters who employed management based on natural processes (Schütz, 2007). In Britain, the Continuous Cover Forestry Group (CCFG) formed shortly after in 1991 with the aim of transforming even-aged plantations into structurally, visually and biologically diverse forests (CCFG, 2011). The social, cultural and ecological importance of forestry was further emphasized at the 1992 “Earth Summit” in Rio, the 1993 Helsinki guidelines and The Lisbon Declaration in 1998 (Warren, 2002). The UK Forestry Standard promotes the use of low impact methods such as CCF (Forestry Commission, 2004) and this is echoed in the Scottish Forestry Strategy which states “low impact systems are currently under-represented in Scotland and a strategic aim of this Strategy is to increase their coverage”(Scottish Executive, 2006). The policy of the National Assembly for Wales is to adopt alternative management systems to clearfelling where they would make a better contribution to ecosystem services (Welsh Assembly Government, 2009). Despite this strong policy foundation it will take time for a knowledge base on continuous cover forestry to be built up regarding its implementation in the UK (Mason *et al.*, 1999). The Glentress Trial Area provides a unique opportunity to increase knowledge and understanding on the application of CCF in upland, coniferous forests.

There have been periodic assessments of stand structure since the start of the Trial Area in an attempt to assess the progress of transformation. The first period of monitoring was from 1952 to 1964 when the Check method was used (Knuchel, 1953); this involves taking diameter measurements for every tree on a periodic basis. However, the Check method is a time consuming survey method estimated to take 10 hours per hectare and was abandoned in 1964 (Malcolm, 1971). Following this, assessment of the progress to transformation was through a series of undergraduate and postgraduate research projects (Wilson *et al*., 1999). The next comprehensive assessment took place in 1990 when a network of permanent sample plots was established.

Whilst the monitoring of the Trial Area has occurred in three discrete periods, management has been continuous. However, there have been difficulties implementing the management plan mainly due to planting failures, deer browsing, breaks in the harvesting plan and uncertainty when assessing natural regeneration. As a result, the estimated transformation period of 60 years was initially extended until 2015 (McIver *et al.*, 1992) and then later to 2033 (Wilson *et al.*, 1999).

Up until 2010, group felling had been the primary silvicultural method used to progress transformation. This has involved the removal of small groups of trees, with 0.1 ha the preferred group size on the upper slopes and 0.2 ha at lower elevations. In the initial phase these groups were planted with young trees but latterly there has been an attempt to use natural regeneration with the aim of reducing costs. However, since Glentress generally has good soils and there has been a tendency for the groups to quickly colonise with grasses and ferns; hence natural regeneration has not always been successful. The most recent management plan for the Trial Area has introduced more flexibility to management, employing variable intensity thinning and reinstating planting as a method of regeneration on the more difficult sites (Kerr *et al.*, 2010a; Kerr *et al.*, 2010b).

There are a number of publications that have focussed on the Trial Area (Wright, 1991; Malcolm, 1992; McIver *et al.*, 1992; Blyth, 1993; Wilson *et al.*, 1999; Kerr *et al.*, 2010a); all of these except Wright (1991) make use of data from the permanent sample plots established in 1990. An assumption made in most of the publications has been that progress in transformation can be assessed using a diameter-frequency distribution. A reverse-J shaped diameter-frequency distribution is commonly observed in stands with an irregular structure (De Liocourt, 1898; Meyer, 1952) and the assumption has been that as transformation proceeds the fit of the diameter distribution will become closer to a reverse-J shape. However, Kerr *et al*. (2010a) examined all the data available for the Trial Area and showed that a reverse-J shaped diameter-distribution had been present in each of the six management units ('Blocks') since the first assessments, which started in 1952. Part of the explanation of this finding is that if a large area (each management unit or 'Block' is about 20 ha) that comprises several even-aged stands of different species and stages of development is assessed, the resulting diameter distribution can be reverse-J shaped. The spatial scale analysed must be taken into account when interpreting reverse-J diameter distributions.

Funding was obtained to reassess the Trial Area in 2008 and the main objectives of this paper are to:

1. Describe the changes in species composition and forest structure that have occurred between 1990 and 2008.

2. Examine future options for thinning the Trial Area to inform the management planning process.

2.2 Methods

2.2.1 Site description

Glentress forest is situated 25 miles south of Edinburgh, approximately two miles east of Peebles (Longitude 3^{o} 9' W, Latitude 55^{o} 40'N). The forest has a total area of 1140 ha with the Trial Area making up 117 ha (Figure 2.1). The data used in this study were collected from permanent sample plots distributed in each of the management units, i.e. Blocks A to F (Figure 2.1). The Trial Area spans an altitudinal range of 240 to 560 metres. The Glentress stream runs approximately north to south and the catchment includes at least part of every Block. In general the soil types, which are derived from Ordovician sediments, can be categorised depending on the topography. On the lower slopes well drained acid brown earths predominate whereas there are podzolic peaty surface-water gleys, often with iron pans, on the upper slopes (Kennedy, 2002). The general aspect of the Trial Area is south and the annual precipitation is between 1000 and 1500 mm (Malcolm, 1992). The main overstorey species are Sitka spruce (*Picea sitchensis* (Bong.) Carr.), Norway spruce (*Picea abies* L.), Douglas-fir (*Pseudotsuga menziesii* (Mirb.) Franco), Japanese larch (*Larix kaempferi* (Lamb.) Carr.) and Scots pine (*Pinus sylvestris* L.). On the upper slopes the ground vegetation is dominated by grass heath, the main component of which is wavy hair grass (*Deschampsia flexuosa* (L.) Trin.) with heather (*Calluna vulgaris* (L.) Hull) appearing in patches. The lower and mid-slopes are characterised by bracken (*Pteridium aquilinum* (L.) Kuhn), ferns (*Dryopteris* spp.) and creeping soft grass (*Holcus mollis* L.) (Malcolm, 1992).

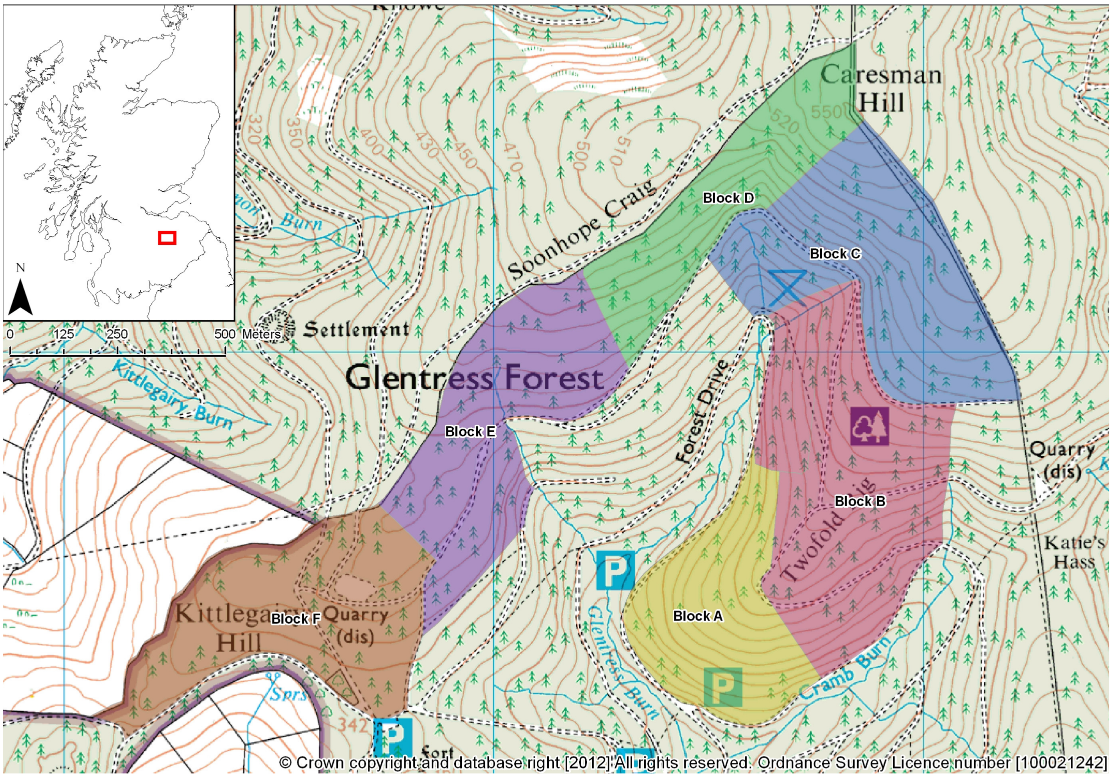


Figure 2.1 Map of the Glentress Trial Area showing Blocks A-F.

<u>2.2.2 Plot assessments</u>

The data used to analyze changes in stand structure between 1990 and 2008 were collected from a reassessment of the network of permanent plots. In Blocks A-E the plot size was 10 by 40 metres. In 1989 the plots in Block F were 10 x 50 metres though when sampled in 2008 only 10 x 40 metres were measured. Each plot was made up of four 10 x 10 metre subplots. However, by 2008, 28 of the original 238 plots had been lost due to a significant area of Block C being cleared (10 plots); the creation of the quarry in Block F (1 plot) and the development of extensive cycle tracks. Two plots in Block E were measured in the 2008 assessment that had been missed in 1990 (Table 2.1).

Table 2.1 The area and number of plots in each Block and sub-Block of the Trial Area.

Block	Area (ha)	Number of plots	Sub-Blocks	Area (ha)	Number of Plots
A	17.8	39	1	4.3	8
			2	5.5	12
			3	8.0	19
B	20.5	32	1	11.5	16
			2	4.6	6
			3	4.4	10
C	18.7	38	1	2.8	6
			2	6.8	15
			3	9.1	17
D	14.2	30	1	5.2	10
			2	9.0	20
E	20.1	40	1	9.0	18
			2	6.0	12
			3	5.1	10
F	22.1	31	1	8.0	13
			2	5.5	10
			3	6.4	6
			4	2.2	2

Within each subplot the following were recorded:

- The diameter at breast height (DBH) and species of every tree (DBH ≥ 7 cm).
- The number, species and DBH of saplings (height ≥1.3 m; DBH < 7cm).
- The number and species of all seedlings (height < 1.3 m).

When the permanent plots were established each Block was composed of between 2 and 4 sub-Blocks, which were used to divide the Blocks into smaller areas and were used to help locate the positions of the plots. These sub-Blocks had not been used in previous analyses but were recorded during the assessment.

In summary, an area of 8.4 ha was assessed in 2008, which is 7.2% of the Trial Area.

2.2.3 Data analysis

Species composition

To ensure the results were comparable with previous studies the tree species were categorised into five groups (Table 2.2). Using these groups the tree species composition was calculated for the Trial Area and each Block. Using the DBH of each tree its individual basal area was calculated. From this the basal area per hectare and by species category was estimated for the Trial Area and each Block. The species groups were also used to quantify the composition and density of seedling and sapling regeneration.

Table 2.2 The Species groups and the species that they contain that were used for the analysis.

Species Group	Species
Spruce	Sitka spruce Norway spruce
Pine	Scots pine Corsican pine (*Pinus nigra* var. *laricio* (Poir.) Maire) Lodgepole pine (*Pinus contorta* Dougl. var. *latifolia* Wats.)
Larch	European larch (*Larix decidua* Mill.)* Japanese larch
Other Evergreen Conifers (OEC)	Western hemlock (*Tsuga heterophylla* (Raf.) Sarg.) Douglas-fir Noble fir (*Abies procera* Lindl.) * Western red cedar (*Thuja plicata* D. Don.) Grand fir (*Abies grandis* Lindl.)
Broadleaves	Wild cherry (*Prunus avium* L.)** Sycamore (*Acer pseudoplatanus* L.) Rowan (*Sorbus aucuparia* L.)** Grey alder (*Alnus incana* (L.) Moench)** Elder (*Sambucus nigra* L.)** Silver birch (*Betula pendula* Roth)** European beech (*Fagus sylvatica* L.) Common alder (*Alnus glutinosa* (L.) Gaertn.) Aspen (*Populus tremula* L.)**

* The species was only present during the 1990 assessment.
** The species was only present during the 2008 assessment.

Diameter distributions

The method used to assess stand structure was to fit diameter distribution data from each sub-Block, Block and the whole Trial Area to a negative exponential regression using Genstat 11 (VSN International Ltd. Hemel Hempstead, UK). The equation takes the form:

$$\mathbf{Y} = \mathbf{k}e^{-\mathbf{ax}} \qquad \text{(equation 1)}$$

This is also closely related to q, the diminution coefficient, which is the ratio of the number of trees in one diameter class to the number of trees in the next larger class.

$$\mathbf{q} = e^{\mathbf{aw}} \qquad \text{(equation 2)}$$

Where: **Y** = the number of trees in a particular diameter class

x = the mid-diameter of a particular diameter class in cm

w = the range of the diameter class in cm

q = the diminution coefficient

a and **k** are constants

The constant **a** describes the slope of the regression and, in the context of CCF, reflects the rate of loss of trees as a result of mortality or thinning from one diameter class to the next larger one. The value of **k** is closely related with that of **a** and determines the 'starting point' of the regression at x = 0, and, in the context of CCF, reflects the necessary recruitment of saplings developing into trees for the structure to be sustainable (Meyer, 1952).

The standard approach to fitting the model in the forest science literature is to use least squares. However, the model can also be fitted using a log-linear Poisson generalised linear model (GLM). The use of least squares regression assumes normality, homogeneity of variance and independence. Although non-linear regression is the most common method of fitting the model in the literature, it is not always the best suited statistically, as the data used often do not meet these assumptions (Chatfield *et al.*, 2009). Therefore, in this study the model has been fitted using both methods to the Trial Area, each Block and all sub-Blocks.

To examine the effect of scale on the fit of the regressions the method used to fit the data from each Block was repeated for geographically distinct subsets of data for each Block, these are referred to as sub-Blocks; there were three for Blocks A, B, C and E, two for D and four for F (Table 2.1). Each of the sub-Blocks used to be a separate compartment that was used for forest management. This analysis used the regression model fitted using least squares and the percentage variance for each subset was compared with the fit at Block level.

Future options for thinning the Trial Area

The second objective of this study was to examine future options for thinning the Trial Area to help inform the management planning process. The new management plan for the Trial Area (Kerr *et al*., 2010b) advocates a method of thinning whereby the number of trees to be removed is calculated based on the differences between actual stand structure and a target structure (both expressed as diameter-frequencies). For example, if the stand data showed that there were more small trees than the target structure then the focus of thinning would be to remove a proportion of small trees.

Target structures were derived using a spreadsheet developed by Clarke (1995). This spreadsheet calculates the regressions described in equations 1 and 2 based on two numbers that are readily understood by forest managers:

- residual basal area – the basal area required after the thinning
- maximum diameter of trees – usually set with reference to local markets

These are specified along with the diminution coefficient (q) which is the ratio between the number of trees in one size class to the number in the next larger class. Clarke's method was used to generate target structures for each Block using values of residual basal area and maximum DBH from the management plan (Kerr *et al*., 2008) and values of q calculated from the 2008 assessment data (the average for the Trial Area in 2008 was used). In order to generate the target structures, Clarke's spreadsheet first calculates the maximum number of trees in the largest diameter class. Following this the number of trees in each smaller diameter class can be found by multiplying by q. This process is then repeated until the numbers of trees in all the diameter classes are calculated. A modification of Clarke's spreadsheet by Kerr (2001) then compares the actual stand structure with the target structure and calculates a 'cutting guide' that specifies the proportion of trees in each of four diameter classes (small, medium, large and very large) that could be removed where the actual structure has more trees than the target structure. The cutting guide is expressed as '1 in X trees' for each of the four diameter classes. The reason for using wide diameter classes is that they are much easier to identify during a marking/thinning operation compared with a larger number of narrower diameter classes.

The most recent management plan for the Glentress Trial Area suggests initial values for the target stand structure of each Block (Kerr *et al.*, 2010b). These values are derived from a historical analysis of the Trial Area carried out by Kerr *et al.*(2010a) and are based on data from the 1990 assessment. The 2008 assessment data suggest that different values of q should be used. As a result, the suggested figures from the management plan were used for basal area and the maximum diameter of trees and the values of q were derived from the 2008 data set, i.e. the baseline scenario. Future thinning options for the Trial Area were examined by comparing five different scenarios with the baseline. The following scenarios were used and are summarized in Table 2.3:

Table 2.3 The baseline thinning scenario and the five other scenarios examined. The target BA, DBH and q values are shown for the baseline scenario.

Block	Parameter	Scenario*					
		Baseline	1	2	3	4	5
A	BA (m^2 ha^{-1})	28		25	22		
	DBH (cm)	60				50	70
	q	1.3	1.2				
B	BA (m^2 ha^{-1})	28		25	22		
	DBH (cm)	60				50	70
	q	1.3	1.2				
C	BA (m^2 ha^{-1})	25		22	20		
	DBH (cm)	50				40	60
	q	1.3	1.2				
D	BA (m^2 ha^{-1})	25		22	20		
	DBH (cm)	50				40	60
	q	1.3	1.2				
E	BA (m^2 ha^{-1})	28		25	22		
	DBH (cm)	60				50	70
	q	1.3	1.2				
F	BA (m^2 ha^{-1})	28		25	22		
	DBH (cm)	60				50	70
	q	1.3	1.2				

* Figures are shown where they differ from the baseline scenario

- Scenario one reduced the value of q for the Trial Area and each Block from 1.3 to 1.2.
- Scenario two reduced the residual basal area by 3 $m^2 ha^{-1}$ for each Block.
- Scenario three reduced the basal area by 6 $m^2 ha^{-1}$ for Blocks A, B, E and F and to 5 $m^2 ha^{-1}$ for Blocks C & D.
- Scenario four decreased the diameter of the largest tree by 10 cm.
- Scenario five increased the diameter of the largest tree by 10 cm.

2.3 Results

2.3.1 Species Composition

Compositional changes for the different species groups are shown in Figure 2.2 and the general trends for the Trial Area are:

- There has been a small increase in spruce, from 64.1% in 1990 to 67.9% in 2008. However, it should be noted that within the spruce category, Norway spruce has reduced by more than 50 % and Sitka spruce has approximately doubled.
- Both larch and pine have decreased, pine from 7.8 % to 3.4 % and larch from 19.3% to 13.1 %.
- Other evergreen conifers (OEC, see Table 2.2) have nearly doubled from 7.6% to 13.5 % and broadleaves have increased their percentage but still make up only a minor component (2.1%).

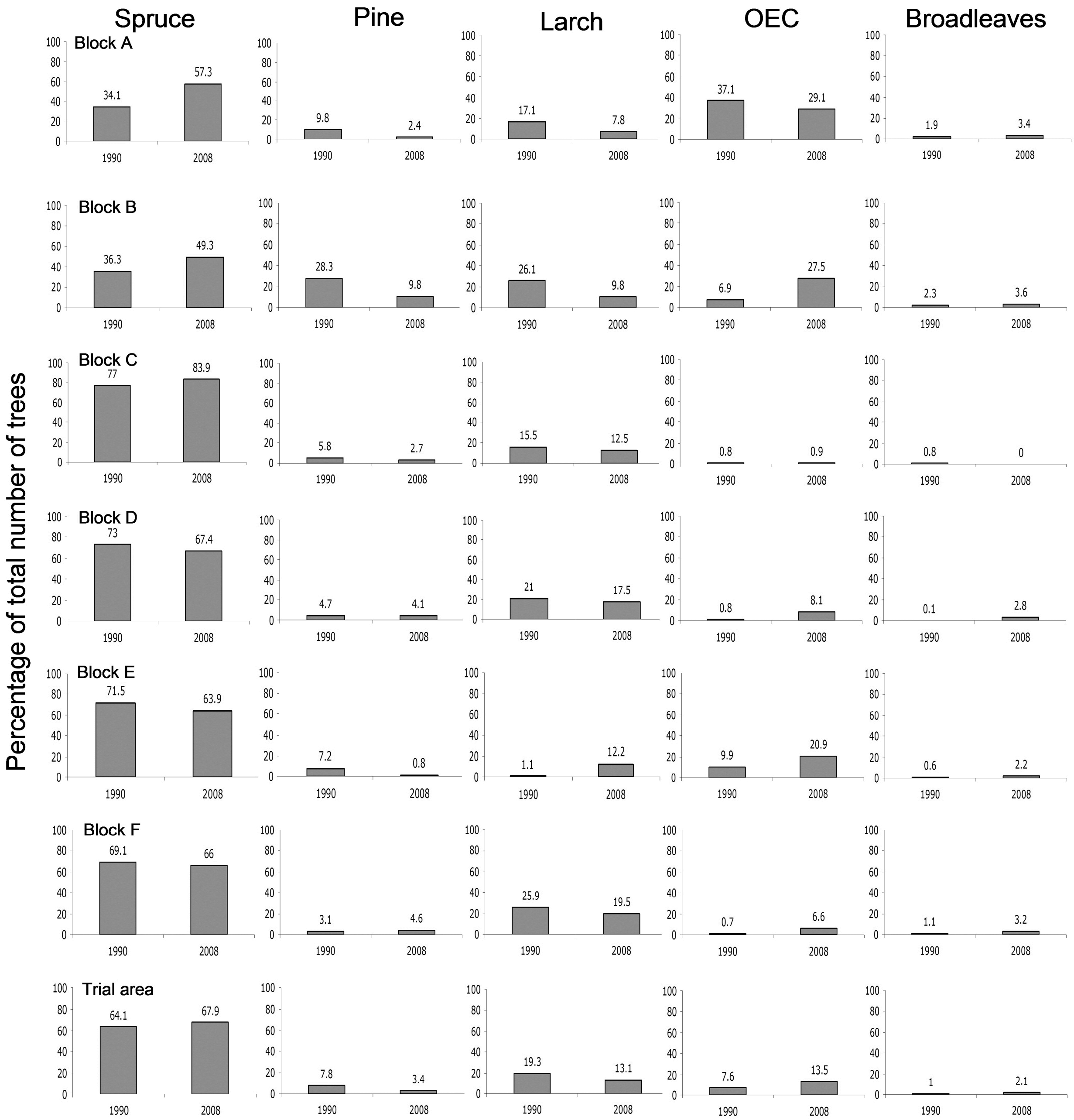


Figure 2.2 Changes in composition of species groups between 1990 and 2008 for each Block and the Trial Area.

Table 2.4 Percentage change of number of spruce trees and basal area in the Trial Area between 1990 and 2008.

	Spruce (% change between 1990 and 2008)	
Block	Number of trees	Basal area
A	+ 68	+347
B	+36	+155
C	+9	0
D	-8	-22
E	-11	+8
F	-4	-2

More detailed trends for each Block are:

Block A

The same general trends as the Trial Area except for OEC and spruce. Block A still has the highest percentage of OEC, but this has decreased from 37.1% in 1990 to 29.1% in 2008. The increase of spruce from 34.1% to 57.3% is a higher proportional increase compared with the general trend (Figure 2.2).

Block B

The trends exhibited by the Trial Area hold true in Block B. The OEC have increased from 6.9% in 1990 to 27.5% in 2008. There is also an increase in spruce, from 36.2% to 49.3%, which is much higher than the increase for the Trial Area (Table 2.4).

Block C

For spruce, pine and larch the trends are fairly similar to that of the Trial Area. However, OEC increased by only 0.1 % during the period between the assessments. Block C is also the only area where the amount of broadleaves has actually dropped, with none being recorded in 2008.

Block D

Larch and pine follow the general trends for the Trial Area. OEC has shown a large increase, from just 0.8% in 1990 to 8.1% in 2008. Broadleaves also increased from 0.1% to 2.8%. There has been a decrease in Spruce from 73% to 67.4%.

Block E

Pine, OEC and broadleaves follow the general trends for the Trial Area. However, it is the only Block where the percentage of larch increased with a modest rise from 10.1% to 12.2% in 2008. In addition the percentage of spruce has decreased between the two assessments.

Block F

All groups follow the trends shown by the Trial Area except spruce and pine. Spruce decreased from 69.1% in 1990 to 66% in 2008 and pine increased from 3.1% to 4.6%.

2.3.2 Basal area

Overall there has been a slight increase in basal area between the two assessments (Figure 2.3). However, at the Block level it becomes apparent that there has been an increase in basal area in every Block except Block D where there has been a decrease from 31.3 to 24.3 $m^2\ ha^{-1}$. The biggest differences in the composition of the basal area occurs in Blocks A and B where there have been large increases in the percentage of spruce accompanied by declines in the percentage of larch and pine (Figures 2.3 and 2.4).

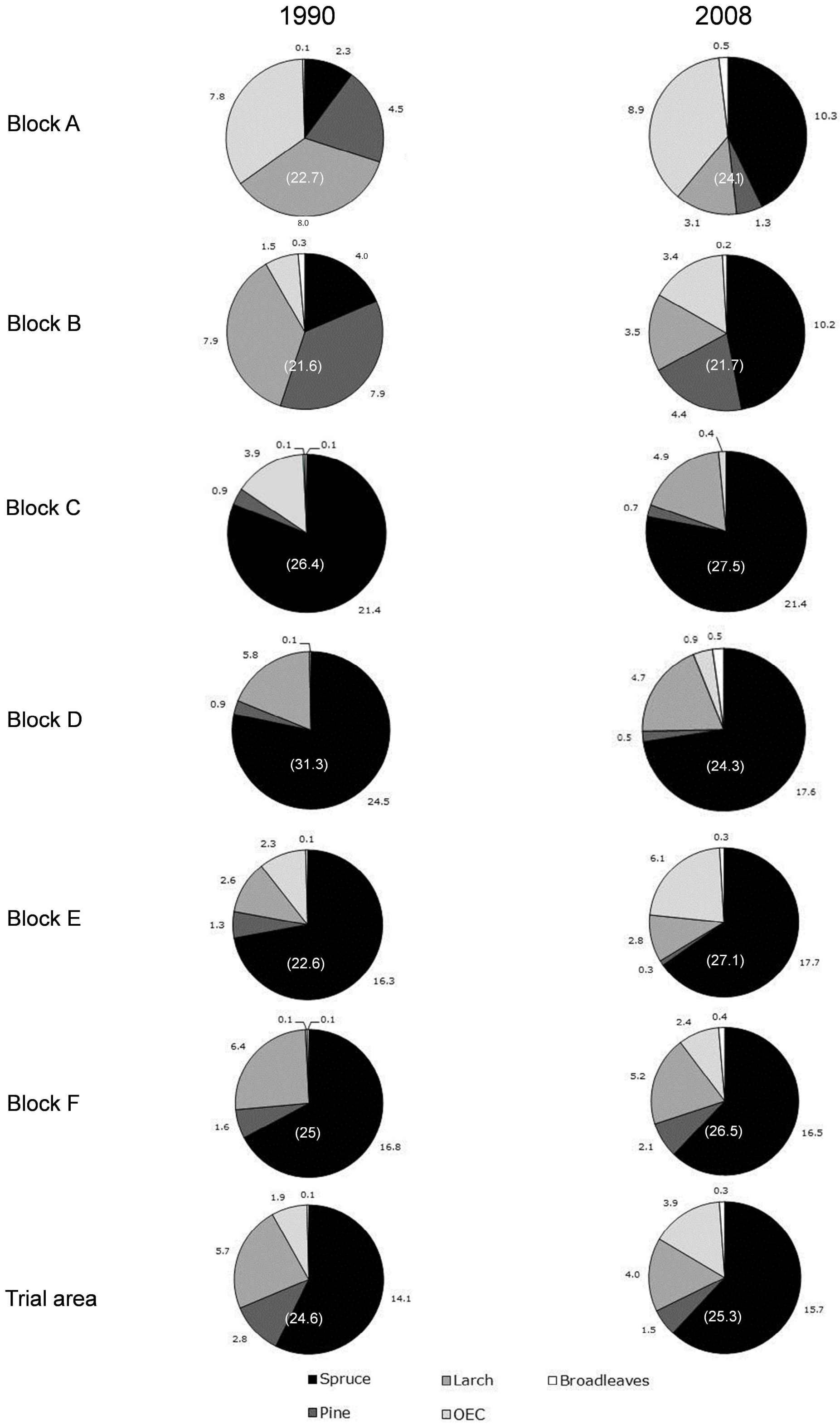


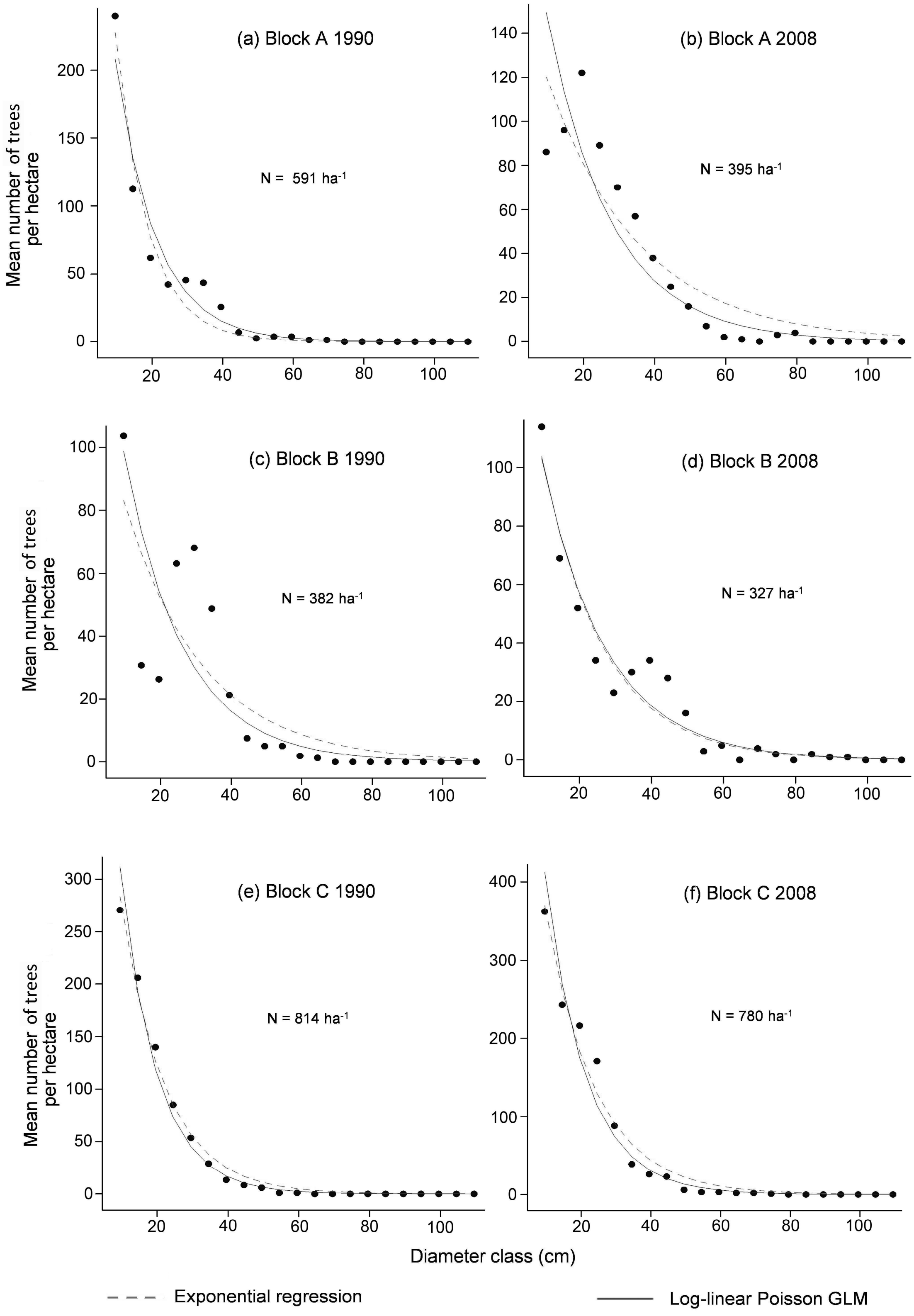
Figure 2.3 Changes in basal area ($m^2\ ha^{-1}$) between 1990 and 2008 for each Block and the Trial Area.

2.3.3 Diameter-frequency regressions

The general trend for the Trial Area is that the reverse-J shape has been maintained (Figure 2.4). However there have been some changes since 1990 for the Trial Area (Table 2.5):

- The value of q has gone down from 1.44 to 1.30.
- The parameter k has reduced from 402 to 209.

The percentage variance explained has declined from 99.5% to 95.6%


(a) Block A 1990
N = 591 ha-1
(b) Block A 2008
N = 395 ha-1
(c) Block B 1990
N = 382 ha-1
(d) Block B 2008
N = 327 ha-1
(e) Block C 1990
N = 814 ha-1
(f) Block C 2008
N = 780 ha-1
Mean number of trees per hectare
Diameter class (cm)
Exponential regression
Log-linear Poisson GLM

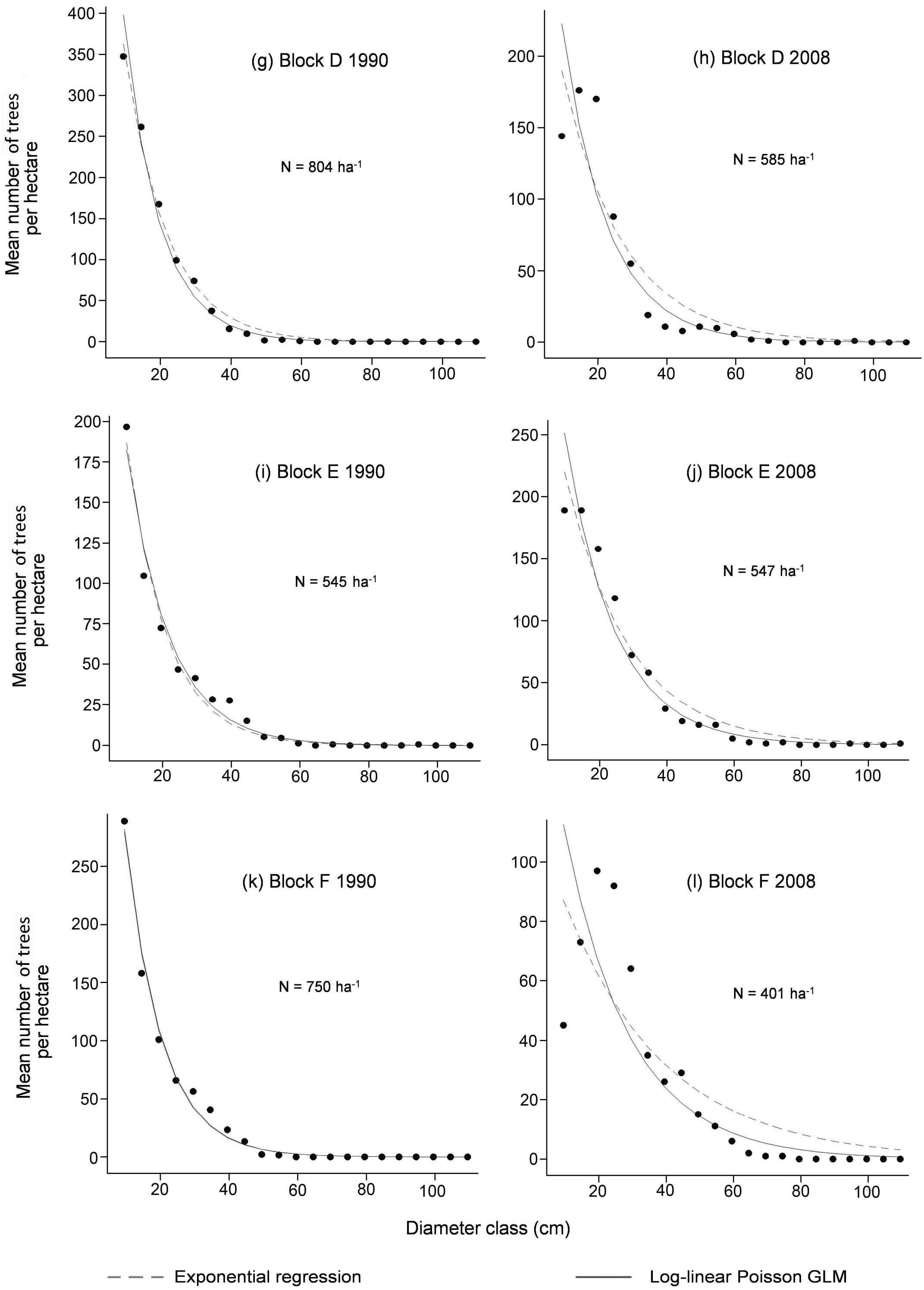


Figure 2.4 Diameter distributions, fitted exponential regressions and log-linear Poisson GLMs for the 1990 and 2008 assessments fitted to each Block.
(Number of trees per hectare from least squares fit; NB, figures are generally higher than those shown in Figure 4 of Kerr et al. (2010) because the new analysis used all trees ≥7 cm; see text)

Table 2.5 Regression parameters from the standard fitting and generalized liner model for the Trial Area and each Block in 1990 and 2008.

	Least squares		**Log-linear Poisson GLM**	
	k		**$\log_e k$**	
	1990	**2008**	**1990**	**2008**
Block A	640	111	6.163	5.088
Block B	127.3	141	5.159	4.924
Block C	609.5	473	6.663	6.417
Block D	796.5	272	6.927	5.949
Block E	427.1	228	5.979	5.7
Block F	686.9	97	6.536	4.993
Trial Area	402.3	209	6.181	5.62
	q		***q***	
	1990	**2008**	**1990**	**2008**
Block A	1.72	1.21	1.53	1.32
Block B	1.25	1.34	1.35	1.34
Block C	1.5	1.42	1.62	1.53
Block D	1.51	1.33	1.64	1.46
Block E	1.55	1.31	1.51	1.40
Block F	1.61	1.18	1.61	1.29
Trial Area	1.44	1.30	1.52	1.40
	% variance		**Deviance**	
	1990	**2008**	**1990**	**2008**
Block A	96.2	84.6	50.72	78.52
Block B	69.8	94	151.0	41.53
Block C	99.1	97.6	27.34	43.89
Block D	99.2	86.2	38.31	88.71
Block E	98.2	95.6	28.03	37.51
Block F	99.1	70.8	35.29	117.0
Trial Area	99.5	95.6	24.84	29.67

It should be noted that the numbers in Figure 2.4 and Table 2.5 for 1990 are different to those in Kerr *et al*. (2010a). The reason for this is that the earlier analysis of the 1990 data did not include trees in the smallest diameter class; this was done to ensure compatibility with data from 1952-1963, when the smallest trees were not measured. In this paper the results of the analysis of all trees ≥7 cm are presented.

The only exception to the general trend was Block B where the values of q, k and percentage variance have all increased. One of the reasons for the poor fit of Block B in 1990 was that there were many more trees between 22 and 37 cm DBH compared with the regression. By 2008 this had become much less pronounced and consequently the percentage variance explained by the fitted regression increased (compare Figures 2.4c and 2.4d).

The main factor contributing to the reductions in the values of q, k and percentage variance is a reduction in the densities of small trees, which was most marked in Blocks A, D, E and F (Figure 2.4). There were also reductions in overall densities of trees in these four Blocks.

From observation of Figure 2.4 there is some evidence that the Poisson GLM appears to produce a better fit than the negative exponential regression. However, the former possibly gives a less useful measure of fit as deviance is not a relative measure.

Visual inspection of the tree frequency plots for each of the sub-Blocks indicates that in all but one (Block F, sub-Block 3, 48.1%) a reverse-J shape is maintained at smaller scales (data not shown). The most consistent is Block E where each of the three sub Blocks shows a small reduction in variance accounted for. However, the other five Blocks have sub Blocks that range between a reduction of 27.7% and an increase of 6.7% (Figure 2.5).

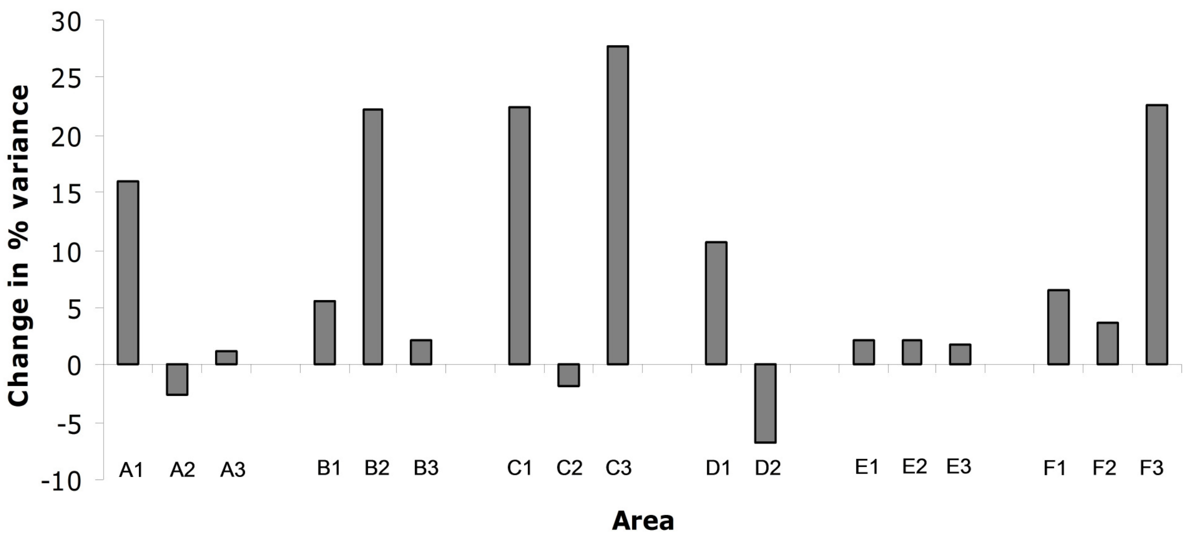


Figure 2.5 The observed difference in percentage variance between Blocks and sub Blocks

2.3.4 Regeneration

The total density of seedlings in the Trial Area has increased by 372 % since 1990 (Table 2.6). In Blocks C and D the increase is by a factor of approximately 10, and in 2008 the species composition is over 90% spruce of which the majority was Sitka spruce. For seedlings, the main species group in Blocks B, C, D and E is spruce, in Block A it is OEC and in Block F it is broadleaves. Other significant species components are broadleaves in Blocks A and B and OEC in Blocks E and F.

Table 2.6 Percentage and density of saplings and seedlings for each Block and the Trial Area in 2008.

	Spruce (%)	**Pine (%)**	**Larch (%)**	**OEC (%)**	**Broadleaves (%)**	**Density 2008 (N ha^{-1})**	**Density 1990 (N ha^{-1})**
Saplings							
A	46.3	-	7.0	22.4	24.3	137	250
B	53.3	-	7.7	19.2	19.8	142	139
C	89.3	-	2.4	1.4	6.9	190	687
D	80.4	2.6	2.6	10.4	3.9	192	348
E	68.6	-	9.7	10.7	11.0	199	294
F	25.2	-	5.2	9.7	60.0	125	304
Trial Area	60.5	0.4	5.8	12.3	21.0	164.2	337
Seedlings							
A	18.7	0.3	16.5	37.9	26.6	210	90
B	50.7	-	10.9	6.5	31.9	235	27
C	96.2	0.1	1.0	0.5	2.3	2117	223
D	92.4	0.5	0.8	1.1	5.1	1139	101
E	67.2	0.9	3.4	20.6	7.9	579	324
F	19.8	2.9	13.2	27.9	36.2	223	189
Trial Area	57.5	0.8	7.7	15.8	18.3	750	159

There has been a decrease of approximately 50% in the density of saplings in the Trial Area between the two assessments. The biggest decrease was in Block C where the density has dropped from 687 saplings per hectare in 1990 to 190 saplings per hectare in 2008. Spruce is dominant in the sapling category for the Trial Area but has shown decreases in some Blocks such as Block F where it now only accounts for 25.2%. Pine and larch have maintained similar levels to those found during the 1990 assessment. There has been an increase in the amount of OEC and Broadleaves in the sapling category. In Block F, broadleaves account for 60% of the saplings measured during the 2008 assessment.

2.3.5 Management scenarios

The results of the management scenarios are shown for all the Blocks in the Trial Area in Table 2.7. The effects of the five scenarios are described relative to the baseline and only thinnings more intensive than 1 tree in 10 are considered.

The following trends were observed:

- The baseline scenario only leads to thinning in the small size category of Blocks C, D and E.
- The main effects of reducing q from 1.3 to 1.2 (scenario 1) is an increase in thinning intensity of small trees in Block E, medium trees in Block A and the felling of all very large trees in Blocks C and D.
- The main effect of reducing residual basal area by 3 $m^2 ha^{-1}$ (scenario 2) is an increase in thinning intensity in the small trees in Block E, the medium trees in Block A and the felling of all very large trees in Block D.
- The main effect of reducing the residual basal area by 6 $m^2 ha^{-1}$ (scenario 3) is generally an increase in the intensity of thinning experienced in scenario two. The exceptions are in Block C and Block F. In Block C there is now the additional removal of all the very large trees and in Block F the very large trees should be thinned.
- The main effect of decreasing maximum DBH by 10 cm (scenario 4) is the removal of all the very large trees in all Blocks. In addition to this, the large trees in Blocks C and D are also totally removed. The other main effect is a reduction in the thinning intensity of small trees in Blocks C, D and E.
- The main effect of increasing max DBH by 10 cm (scenario 5) is an increase in thinning intensity of small trees in Block E and medium trees in Blocks E and F.

Table 2.7. Cutting guides for the baseline and the five scenarios.

Area	Diameter class*	Actual stand (No. trees ha^{-1})	Effects of scenarios on thinning prescriptions**					
			Baseline	Scenario 1	Scenario 2	Scenario 3	Scenario 4	Scenario 5
Block A	Small	252	NT	LT	NT	NT	NT	NT
	Medium	106	LT	95 (1 in 10)	92 (1 in 8)	81 (1 in 4)	NT	LT
	Large	31	NT	NT	NT	NT	NT	NT
	Very large	6	NT	NT	NT	NT	0 (1 in 1)	NT
Block B	Small	210	NT	NT	NT	NT	NT	NT
	Medium	68	NT	NT	NT	NT	NT	NT
	Large	37	NT	NT	NT	NT	NT	NT
	Very large	9	NT	NT	LT	7 (1 in 6)	0 (1 in 1)	NT
Block C	Small	653	314 (1 in 2)	289 (1 in 2)	341 (1 in 2)	310 (1 in 2)	528 (1 in 5)	314 (1 in 2)
	Medium	101	LT	NT	LT	91 (1 in 10)	NT	LT
	Large	21	NT	NT	NT	NT	0 (1 in 1)	NT
	Very large	6	NT	0 (1 in 1)	NT	0 (1 in 1)	0 (1 in 1)	NT
Block D	Small	482	314 (1 in 3)	289 (1 in 3)	341 (1 in 3)	310 (1 in 3)	NT	314 (1 in 3)
	Medium	71	NT	NT	NT	NT	NT	NT
	Large	24	NT	NT	NT	NT	0 (1 in 1)	NT
	Very large	8	NT	0 (1 in 1)	0 (1 in 1)	0 (1 in 1)	0 (1 in 1)	NT
Block E	Small	409	352 (1 in 7)	242 (1 in 2)	314 (1 in 4)	277 (1 in 3)	NT	305 (1 in 4)
	Medium	99	NT	LT	LT	81 (1 in 5)	NT	90 (1 in 10)
	Large	32	NT	NT	NT	NT	NT	NT
	Very large	6	NT	NT	NT	NT	0 (1 in 1)	NT
Block F	Small	248	NT	LT	NT	NT	NT	NT
	Medium	101	NT	LT	LT	81 (1 in 5)	NT	90 (1 in 9)
	Large	44	NT	NT	LT	37 (1 in 6)	LT	LT
	Very large	8	NT	NT	NT	7 (1 in 9)	0 (1 in 1)	NT

* Diameter classes are: small (7-26.9 cm); medium (27 – 41.9cm); large (42 – 56.9cm); very large (> 57cm)
**Thinning prescriptions: NT-no thinning; LT-light thinning (less intense than removing 1 tree in 10); where thinning is recommended the first figure is the residual number of trees to be left after thinning and the intensity of removal follows in brackets (1 tree in X).

2.4 Discussion

2.4.1 Species composition

The first objective of this study was to assess whether there had been a change in species composition and stand structure between the 1990 and 2008 stand assessments. The 2008 assessment confirms that Sitka spruce is now the dominant species in the Trial Area. This is somewhat masked in the analysis as both Norway and Sitka spruce are analysed together, because although there has been an increase in Sitka spruce, this is often accompanied by a decrease in Norway spruce. The increase in Sitka spruce is unsurprising as in addition to it being of an age where seed production is at its maximum, it also regenerates well in an upland, Scottish climate (Nixon and Worrell, 1999; Gosling, 2007). Although research suggests that coning of Sitka and Norway spruce is synchronous in the UK (Broome *et al.*, 2007), in the Trial Area Norway spruce does not regenerate as well as Sitka. Norway spruce maximum seed production can be as late as 60 years where as Sitka spruce maximum production usually occurs by 50 years. Furthermore Norway spruce produces a lower number of viable seeds than Sitka spruce (Matthews, 1955; Gordon, 1992; Gordon and Faulkner, 1992). The conifers classified as OEC continued to account for between six and nine percent between 1952 and 1990 (Kerr *et al.*, 2010a). However, between the 1990 and 2008 assessments their numbers nearly doubled. The OEC category contains species that are intermediate to shade tolerant such as western hemlock, noble fir and Douglas-fir (Mason *et al.*, 1999; Coates, 2000; Hale, 2004) and the current management plan suggests all future planting should be of these species as a way of diversifying species composition. The composition of pine and larch has continued to decline and this is probably associated with the fact that these species have not been planted and natural regeneration is scarce.

Whilst it is clear that there have been changes it is very difficult to establish why they have occurred due to patchy record keeping. During the period between the two assessments, the management at the Trial Area was prescribed by the University of Edinburgh but carried out by the local Forest District. For many of the years between 1990 and 2008 there are records of the prescribed management but no confirmation of the interventions. It is imperative that if changes in stand structure are to be correctly interpreted, accurate records of management must be kept. Hopefully, now that a long-term management plan has been implemented record keeping will improve (Kerr *et al.*, 2010b).

2.4.2 Basal area

There has been a small increase in basal area between the 1990 and 2008 assessments for the Trial Area. Four of the Blocks show an increase of between 0.1 and 1.5 m^2 ha^{-1}. However there is a larger increase of 4.5 m^2 ha^{-1} in Block E and a decrease of 7 m^2 ha^{-1} in Block D. As changes in basal area are driven by tree growth and thinning, the results indicate that these two processes are roughly in balance.

Basal area is of key importance in CCF as it can be used as an indicator of canopy openness. Canopy openness affects the amount of light received by both ground flora and regenerating seedlings. Therefore, management tries to ensure that enough light reaches the ground to allow sufficient seedling growth but not so much as to promote competing vegetation. In even-aged stands the timing of thinning interventions is established through basal area and top height assessments and is well established (Rollinson, 1985). However, even-aged threshold basal areas do not take natural regeneration into account. Hale (2004) suggests critical basal areas for several species to achieve 50 percent of the growth that would be achieved in full light. These values range from 20 m^2 ha^{-1} for larch up to 40 m^2 ha^{-1} for western hemlock.

In the Glentress management plan (Kerr *et al.*, 2010b) target basal areas of 28 m^2 ha^{-1} have been chosen for Blocks A, B, E and F and 25 m^2 ha^{-1} for Blocks C and D. The reasoning for this was that Blocks C and D have poorer soils and therefore the ground flora should not grow so prolifically if basal area is reduced. The values chosen are not dissimilar to those found at Faskally (near Dunkeld), the only other remaining trial established by Mark Anderson, where the basal area has decreased from 32 m^2 ha^{-1} in 1997 to 28 m^2 ha^{-1} in 2009 (Cameron and Hands, 2010). Meyer (1943) found that in seven different types of selection forest in Switzerland the basal area varied from 22.1 to 30.9 m^2 ha^{-1}. All the values in the Trial Area currently fall within this range. Future assessments of basal area will indicate whether the values chosen will need to be modified.

2.4.3 Diameter-frequency regressions

Previous studies (Malcolm, 1992; Blyth, 1993; Wilson *et al.*, 1999) have shown that the Trial Areas diameter distribution can be described by a negative exponential regression. The 2008 assessment confirms that a reverse-J shaped diameter distribution is still present in the Trial Area and each of its Blocks. However, both the value of q and the percentage variance explained by the fitted regression have decreased between the 1990 and 2008 assessments.

The value of q has been decreasing since the first assessment in 1952 (Kerr *et al.*, 2010a) and this trend has continued in the 2008 assessment. For the Trial Area the value of q has fallen from 1.46 in 1990 to 1.3 in 2008. All the Blocks have shown a decrease except for Block B which has increased from 1.18 to 1.33. One probable reason for this increase is that in 1990 the diameter distribution of Block B was quadratic but in 2008 the fit to a negative exponential is much better. The range of q values fits with the typical range of 1.3 to 1.6 found in irregular forests of continental Europe (Gul *et al.*, 2005). However, Schaeffer *et al.* (1930), who defines 1.5 as the maximum value of q for selection forests with five centimetre diameter classes, states that a spruce dominated stand should have a q value near the maximum. Another one of Professor Anderson's trials at Faskally was assessed in 2009 and produced a q value of 1.4, which also is a decline from previous assessments (Cameron, 2007; Cameron and Hands, 2010).

The percentage variance has decreased for the Trial Area and all Blocks other than Block B between 1990 and 2008. For most Blocks the reduction is small with the percentage variance still being over 84%; however, the percentage variance in Block F has reduced by 28%. A contributing factor is likely to be that in Block F there has been extensive development of mountain-bike trails and seven of the 38 permanent sample plots have been lost, which has reduced the sample size.

The results show that there has been a decline in the density of trees in the Trial Area and there are problems with the recruitment of saplings into the smallest diameter class of trees. As the basal area of the Trial Area has remained relatively constant it indicates that individual tree basal area has increased. For a sustainable CCF structure it is necessary to find a balance of the development of big trees and the recruitment of small trees (Schutz, 2001). The results indicate that there is a problem with recruitment and considering the problems of seedlings developing into saplings (see section 2.4.4) this may continue in the future.

Kerr *et al.* (2010a) showed that a reverse-J shaped diameter distribution was present at the Block scale in the data from the first measurement cycle between 1952 and 1957. However, reverse-J distributions can result from looking at large areas that contain even-aged stands of different species at varying stages of development (Rubin *et al.*, 2006; Kerr *et al.*, 2010a). This study was the first time that diameter distributions have been analyzed at sub-Block scale. The analysis at the sub-Block scale has shown that the reverse-J shape is maintained (% variance accounted for > 80%) in 9 of the 18 Areas. From our observations the areas with a % variance lower than 80% tend to include areas where mountain bike development has occurred or that have not been thinned. In order to claim that transformation of the Trial Area was complete it may be necessary to examine stand structure at a much finer scale than has been possible here and this would have implications for sampling.

2.4.4 Regeneration

A much higher density of seedlings were recorded during the 2008 assessment than in 1990. However, the majority of these seedlings were in Blocks C and D and most of these were spruce (mostly Sitka spruce). The large increase in the number of Sitka spruce seedlings may be explained by a number of factors. One of these is the age of tree. Sitka spruce does not start to produce seed until it reaches 30 to 40 years of age (Nixon and Worrell, 1999; Malcolm *et al.*, 2001); however, it is not until an age of 40 to 50 years that it achieves maximum seed production (Matthews, 1955). Much of the higher elevation Sitka spruce in Blocks C and D were less than 40 years old at the time of the 1990 assessment. However, by 2008 many of the trees would have reached maximum seed production. In addition, the poorer soils in Blocks C and D mean that there is much less competition from competing ground flora and Sitka spruce can withstand a higher degree of leader browsing than many other conifer and broadleaf species (Hart, 1991).

Although there were many more seedlings found during the 2008 assessment, there were actually fewer saplings. The diameter distributions for the Blocks and sub-Blocks show that in many cases there are too few trees in the smallest diameter class for 2008, indicating that recruitment from the sapling stage is insufficient. Work carried out in 2009 at the Trial Area has shown that sapling survival is low at just 37% (Kerr and Mackintosh, 2012). There are several reasons that mortality takes place between the seedling-sapling and sapling-small tree life stages but the most likely seems to be browsing by deer. Warren (2002) suggests that if deer exceed 4 to 8 per km^2 then either fencing or culling needs to take place which can be very expensive. On the other hand, Gill (2000) suggests that densities of 4 to 7 per km^2 are acceptable. At densities lower than 4 per km^2, deer are actually thought to promote regeneration as they create small bare patches suitable for regeneration and reduce vegetation competition (Warren, 2002). At Glentress deer densities are likely to exceed these threshold densities as little or no deer control is possible due to intensive use of the forest by mountain bikers.

2.4.5 Future management scenarios

The second objective of the study was the investigation of potential management strategies. The method of doing this was to compare a target stand structure to the actual stand structure. This is a relatively new method for forest management in Britain and requires some expert knowledge of the correct values of basal area, maximum diameter and q to generate a target structure that is realistic and suitable for management objectives. In the case of basal area the values are generally much lower than those used in even-aged management and need to consider the requirements of natural regeneration (Hale *et al.*, 2004). Values for maximum DBH can be chosen based on local timber markets or stability considerations (Gardiner *et al.*, 2004). Values of q can be selected based on data from assessments on a specific stand, similar stands or published values. In this respect the Glentress Trial Area makes a significant contribution to our understanding of the range of target structures to use in upland conifer forests managed using continuous cover.

The scenarios produce different marking guides and the results make clear the importance of selecting informed values of basal area, maximum DBH and q. Having clear management objectives is essential as this will affect the parameter values chosen. For instance, if it was decided that light demanding species such as larch and Scots pine were to be a continuing element within the Trial Area, the basal area would need to be reduced to levels similar to those used in scenario 3 (Hale, 2004).

The sawmill which processes much of the timber from Glentress can now process trees up to 70 cm DBH (personal communication, C. Tracey, February 2011). As a result, scenario 5 is now a viable option for management and is likely to be compatible with management objectives as it will result in a more varied structure and enhance aesthetic value. Scenario 4, which results in felling all the trees > 40 or 50 cm, could result in a loss of structural diversity and in some mature areas may result in clearfelling. It should be stressed that the marking guide is only guidance. If the marking guide prescribes felling all large trees this will lead to a loss of the main sources of seed in the stand and is unlikely to be a good idea and may indicate the target structure should be changed. Another problem with the marking guide is that it uses 15 cm classes to group information from three of the diameter classes used to produce the target structures. This may lead to problems, for example, if there are too few trees in the smallest 5 cm diameter class some of them may be felled or if there are too many trees then not enough may be felled, as the marking may target the larger more valuable trees. Despite this, with training, knowledge of the stand and an accompanying set of felling rules the marking guide could be used to help forest managers with tree selection.

2.5 Conclusion

Spruce, the majority of which is Sitka spruce, is beginning to dominate the Trial Area. It already occupies the largest percentage of the overstorey and in 2008 had the highest number of seedlings and saplings. If the stand is to remain diverse in terms of species then there will need to be interventions. When marking trees Sitka spruce should be marked for removal where possible. This should also apply to any respacing that is required in dense natural regeneration. If planting becomes necessary other suitable species should be considered instead of Sitka spruce. The alternative would be to allow the higher elevation areas to be taken over by Sitka spruce and accept an irregularly structured monoculture.

Blocks A, D, E and F all show too few trees being recruited from the sapling stage. This is despite the much higher number of seedlings being recorded during the 2008 assessment. This result is a concern and the reasons for it should be investigated. Should deer densities prove to be the problem, increased control should be implemented, or protection for seedlings such as fencing should be considered.

In the past the claim that the Trial Area is approaching an irregular structure was based on fitting negative exponential regressions to the diameter distributions at the Block scale. The 2008 assessment has shown that despite changes in tree density, q and the percentage variance, the reverse-J shaped distribution is still present. In 2008, the Area analysis shows that a negative exponential distribution is generally adhered to, although with a lower percentage variance, which indicates a truly irregular structure. However this varies throughout the Trial Area and much work is still necessary, especially in the higher elevation areas of Blocks C and D.

The management scenarios raise several interesting points regarding future management of the Trial Area. The main point is that management of CCF stands need not be complicated. The marking guides produced by the spreadsheet can provide simple prescriptions that provide a starting point for management. However, it is essential that the parameter values for maximum DBH, q and basal area are chosen based on the stand and its management objectives. Furthermore, the cutting guide produced is only guidance and should only ever be used in conjunction with knowledge of the stand itself.

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Chapter 3

Future Management of the Glentress Trial Area using the concept of Equilibrium Growing Stock

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Abstract

The Glentress Trial Area provides a unique source of information for the management of upland, coniferous, continuous cover forestry (CCF) in the UK. Despite the increasing popularity of CCF since the early 1990s there have been very few studies investigating the use of the Equilibrium Growing Stock (EGS) concept under UK conditions. The EGS has two main components. The first is to establish the state of the current growing stock which varies according to site conditions and species composition. The second is to analyse the distribution of the growing stock by diameter class. In theory, a stand in an equilibrium state will have a stable growing stock and volume distribution. It is then possible to harvest a sustainable yield i.e. the annual increment.

For an EGS to be established it is imperative that volume can be estimated accurately. Volume estimation was achieved through the development of a local volume table for Sitka spruce and the use of established relationships for other species.

The Trial Area growing stock showed a small increase in volume between the 1990 and 2008 assessments. However, at the Block scale there were both increases and decreases of greater magnitude. In addition, the growing stock was of a lower volume than values reported from continental Europe. The volume–diameter class distribution shows a decrease in volume in the smallest diameter class and an increase in the largest diameter class between the two assessments. Whilst the volume distribution is still not within the range outlined by Schutz (2001a), it is shifting towards a distribution consistent with that found in Continental Europe. However, differences in species composition and climate found in the UK may result in a volume distribution quite different to those found in continental Europe. Only further periodic assessments of the Trial Area will result in an example target volume distribution that forest managers in the UK can use to manage for sustainable yield.

3.1 Introduction

CCF is an approach to forest management that generally favours two or more canopy layers, an avoidance of clearfelling (areas greater than 0.25 hectares), natural regeneration and a mixture of species. The approach is currently being encouraged by policy as part of a strategy to diversify forests, which in the past have been dominated by single species even-aged stands (United Kingdom Woodland Assurance Standard (Forestry Commission, 2011a); UK Forestry Standard (Forestry Commission., 2011b)). However, there are limitations to the implementation of CCF in Britain including windthrow and unfavourable conditions for natural regeneration (Mason *et al.*, 1999). In addition, there is a further significant limitation: a lack of knowledge and experience of CCF amongst forest managers. CCF management in areas of continental Europe does not have this constraint as CCF has been widely used for long periods of time and forest managers have a good knowledge of how to implement a wide range of silvicultural systems (Helliwell, 1997; Pommerening and Murphy, 2004).

In these introductory stages of CCF management in the UK, forest managers require clear guidance on how to transform even-aged stands to continuous cover (Mason and Kerr, 2004) and, once transformed, how to manage CCF stands (Kerr, 2002). A number of studies in the recent past have helped develop a knowledge base for this in Britain (Hart, 1995; Mason *et al.*, 1999; Wilson *et al.*, 1999; Malcolm *et al.*, 2001; Kerr, 2002; Hale and Kerr, 2009; Poore and Kerr, 2009b; Cameron and Hands, 2010). However, one method of managing complex CCF stands that has only received a small amount of attention is the concept of EGS (Paterson, 1958; Poore, 2007; Poore and Kerr, 2009b). A stand which is in equilibrium is in a theoretical state where a sustainable timber increment is generated from a diameter distribution which remains broadly constant due to sufficient recruitment of young trees (Schutz, 2001b). At the stand level this equilibrium or 'target' structure is formulated for a species and site in terms of the growing stock (usually expressed in volume per hectare) and its distribution across broad diameter classes. Hence the EGS will vary with site and species; for example, a shade tolerant stand may have a higher proportion of the volume located in the small diameter class. In order to establish the EGS the first step is to determine an appropriate ‘growing stock’ in terms of volume per hectare (Kerr, 2002). Secondly, broad diameter classes (typically three) are chosen and the percentage of the stand volume in each diameter class is calculated (Poore and Kerr, 2009a). The management of a stand is then a process of comparing the structure of a stand against a target EGS to inform future thinning and other silvicultural operations in the stand. The fact that there are usually only three diameter classes ensures the method is relatively straightforward to apply in the field. For example, in the Swiss Jura a common target volume distribution is a 20, 30 and 50 % split across the three diameter classes of small, medium and large sized trees (Schutz, 1997; Schutz, 2002a). These volume distributions vary depending on the overall standing volume which can vary from 350 to 500 m^3 ha^{-1} for Silver fir (*Abies alba* Mill.) - Norway spruce (*Picea abies* (L.) Karst.) to 150 to 170 m^3 ha^{-1} for sycamore (*Acer pseudoplatanus* L.) - ash (*Fraxinus excelsior* L.) mixed woodlands. The variability in the volumes is due to differing site and species growing potentials and regeneration capacities (Schutz, 2002b).

As the use of EGS relies on the allocation of volume to diameter classes, it is imperative that volume can be estimated accurately, ideally from an easily measurable attribute such as diameter at breast height (DBH). The relationship between DBH, basal area and tree volume is already well established in the UK for the majority of commercially grown species (Matthews and Mackie, 2006). However, these relationships were based on trees growing in even-aged stands and it is unclear whether they should be applied in CCF stands. Trees in CCF stands experience different growing conditions, such as an altered light regime, and this can affect the form of the stem and hence the relationship between diameter and volume (Waring, 1987; Nilsson and Gemmel, 1993; Pape, 1999). Therefore using the established DBH-volume relationships may result in biased volume predictions.

The Glentress Trial Area presents an excellent opportunity to gain knowledge in the management of CCF. It was established in 1952 with the overall aim of transforming even-aged stands to an irregular structure using a group selection system over a 60 year period (Anderson, 1955). Although monitoring of the transformation has been sporadic (1952-1964, 1990 & 2008), the management of the Trial Area has been continuous making it the longest running trial of transformation to CCF in the world (Kerr *et al.*, 2010a). Recent assessments of the Trial Area in 1990 and 2008 provide an opportunity to investigate the use of EGS in an upland, conifer forest, building on experience from the rest of Britain (Paterson, 1958; Poore, 2007; Poore and Kerr, 2009b) and continental Europe (Schutz, 2001a; Boncina *et al.*, 2002; Schutz, 2002b; Medarevic *et al.*, 2010).

There were two main objectives to this study:

1. To examine how the concept of Equilibrium Growing Stock (EGS) could be applied to the future management of the Glentress Trial Area.

2. To produce a local volume table for Sitka spruce at the Glentress Trial Area and compare results with published volume tables developed for even-aged stands.

3.2 Methods

3.2.1 Site description

The study took place in the Glentress Trial Area (Figure 3.1) where transformation of even-aged stands to continuous cover has been carried out since 1952. The Trial Area is approximately 120 hectares and is divided up into six Blocks (historically called Blocks); the main species are Douglas-fir (*Pseudotsuga menziesii* (Mirb.) Franco) (6.4%), Japanese larch (*Larix kaempferi* (Lamb.) Carr.) (13.1%), Norway spruce (24.6%), Scots pine (*Pinus sylvestris* L.) (2.2%) and Sitka spruce (*Picea sitchensis* (Bong.) Carr.) (43.3%). There are also a number of other conifer and broadleaf species. A detailed description of the site and analysis of the progress of transformation up to 1990 can be found in Kerr *et al*. (2010a).

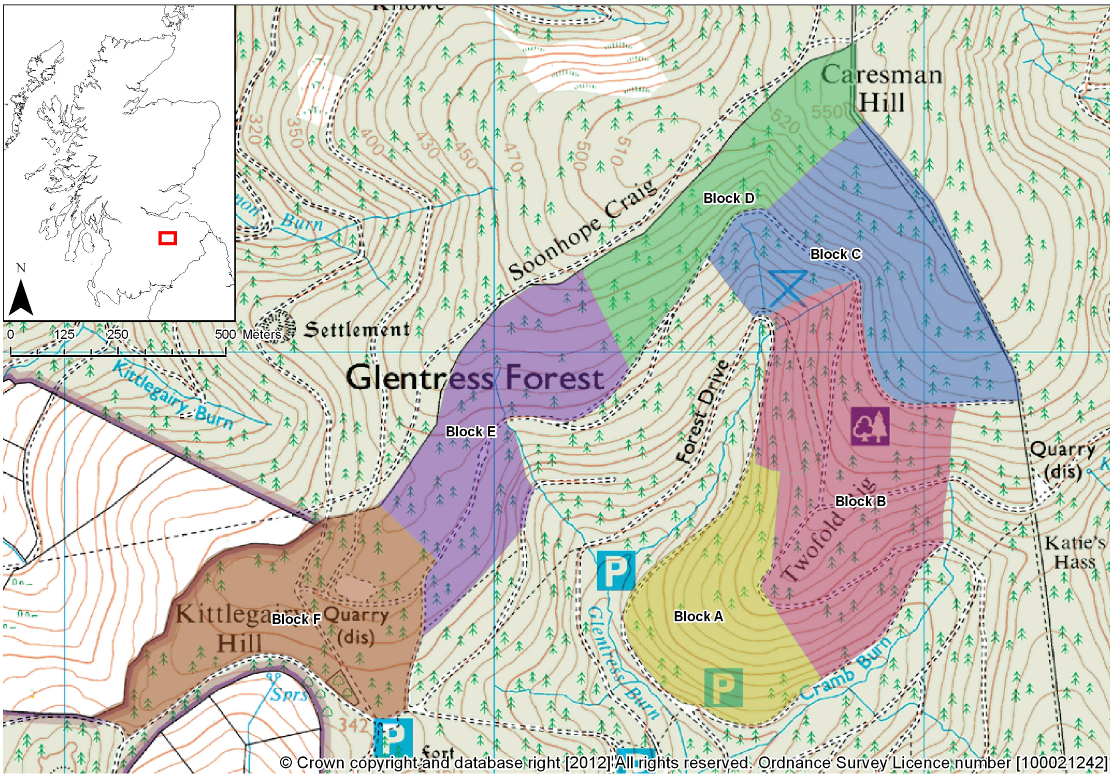


Figure 3.1 Map of the Trial Area showing Blocks A-F.

3.2.2 Volume estimation

The aim was to have an accurate method of estimating volume for all species present in the Trial Area. Matthews and Mackie (2006) recommend the use of local volume tables wherever possible; however, resources were constrained and this meant it was only possible to produce a local volume table for the main species, Sitka spruce. This was supplemented by a second method of estimating volume using tariff numbers for other species. Single tree tariff numbers for individual trees were calculated using DBH and height data. An average tariff number for the stand was then calculated by taking the mean of the individual tariff numbers. The stand tariff number was then used to estimate individual tree volumes using DBH. A mixture of these two approaches was used to estimate volume for all species in the Trial Area as shown in Table 3.1.

Table 3.1 The method of volume estimation used for each species. The volume of bracketed species is calculated using the method established for the un-bracketed species.

Species	Method of volume estimation
Sitka spruce {Norway spruce}	Local volume table
Japanese larch {Hybrid larch}	Abbreviated tariff (C6) as described in Matthews & Mackie (2006)
European larch	Abbreviated tariff (C6) as described in Matthews & Mackie (2006)
Douglas-fir {Western red cedar Western hemlock Grand fir noble fir (1990 only)}	Abbreviated tariff (C6) as described in Matthews & Mackie (2006)
Scots pine {Lodgepole pine Corsican pine (1990 only)}	Abbreviated tariff (C6) as described in Matthews & Mackie (2006)

Local volume table

Philip (1994) states that when creating a local volume table for even-aged stands a representative sample of 50 trees should typically give a mean volume with $\pm$ 10% confidence limits at a probability of $p = 0.05$. The numbers of volume sample trees sampled during the study are shown in Table 3.3.

To ensure trees were sampled throughout the diameter range four size classes were used. Analysis of the 2008 permanent sample plot assessments showed that only five Sitka spruce are over 80 cm DBH (the maximum being 94.2 cm) (Mackintosh *et al.*, 2011). As a result the diameter-classes were defined as small (7 cm to 24.9 cm DBH), medium (25 cm to 42.9 cm DBH), large (43 cm to 60.9 cm DBH) and extra large (over 61 cm DBH). These diameter classes were chosen based on the diameter-frequency distribution of the Trial Area in 2008. This showed that about 99 % of the recorded trees were contained within the 7 – 61 cm range. However, so that the local volume table was applicable to larger trees an extra large diameter class was also created.

To distribute these diameter-classes throughout the Trial Area eight or nine sampling points were randomly located in each of the six Blocks using ArcGIS 9.2 (ESRI, Redlands, California, USA) and were randomly assigned a diameter class. In the field, these points were located using a hand-held global positioning system (GPS) (Garmin etrex Legend, Garmin, Olathe, Kansas, USA) and then the nearest Sitka spruce of the correct diameter class was located, marked and its position recorded. DBH was measured standing and felled tree length was measured using a standard measuring tape to estimate height. To accurately assess the volume of each felled tree the diameter of one-metre sections of the main stem of the tree were measured down to 7 cm top diameter using a standard girth tape. The volume of each section was calculated using each of the following formulae:

Newton's formula: $$v = \frac{\pi L(d_1^2 + 4d_m^2 + d_2^2)}{24} = \frac{L(g_i + 4g_m + g_2)}{6}$$ (equation 1)

Huber's formula: $$v = \frac{\pi L d_m^2}{4} = Lg_m$$ (equation 2)

Smalian's formula: $$v = \frac{\pi L(d_1^2 + d_2^2)}{8} = \frac{L(g_1 + g_2)}{2}$$ (equation 3)

Where:
d_1 = Diameter at base of log, m
g_1 = cross-sectional area at base of log, m^2
d_m = Diameter at the midpoint of log, m
g_m = cross-sectional area at midpoint of log, m^2
d_2 = Diameter at the top of log, m
g_2 = cross-sectional area at top of log, m^2
L = Log length, m
v = Volume of log, m^3

As Newton's formula requires a top, mid and bottom diameter and Huber's formula requires a midpoint diameter, the volume was calculated in two-metre sections for these formulae. The timber volume of each tree was calculated as the sum of all the sectional volumes.

Tariff number

This method of volume estimation was used for Douglas-fir, Scots pine and larch (*Larix* spp.). The guidance in Matthews and Mackie (2006) is that 32 trees should be sampled for each species in variable stands greater than 10 hectares. To determine the location of these trees the Forestry Commission sub-compartment database was used to identify where each species was present and 32 sampling points were randomly assigned within these areas in a similar way to the diameter-class sampling [using ArcGIS 9.2 (ESRI, Redlands, California, USA). In the field these sampling points were located using a Garmin Etrex Legend GPS (Garmin, Olathe, Kansas, USA)]. The nearest tree of the correct species was then sampled providing it was over 10 cm DBH and not within 10 m of the Trial Area boundary. For each tree the DBH was recorded using a DBH tape and total height was measured using a Vertex (Haglöf Sweden AB, Långsele, Sweden). Two heights were recorded for each tree, wherever possible, at an angle of 180^{o} to one another and the average was then calculated.

Table 3.2 The tariff numbers and coefficients used in their calculation for each species.

Species	**Tariff number**	**Coefficients**		
		a	**b**	**c**
Douglas-fir	31	10.397480	1.477313	-0.32565
European larch	28	5.562167	1.908473	-0.42657
Japanese larch	28	8.478127	1.788768	-0.44820
Scots pine	28	9.817387	1.177486	-0.11417
Sitka spruce	26	8.292030	1.771173	-0.41651

To estimate the tariff number for each species, first the tariff number for each individual tree was calculated:

$$\text{Tariff number} = a + b*H + c*DBH \qquad \text{(equation 4)}$$

Where *a, b* and *c* are empirical coefficients unique to each species (Table 3.3), H is the total height of the tree and DBH is the diameter at breast height. The individual tree tariff numbers were then added up and divided by the total number of trees to give a mean tariff number for the species. A tariff number was also calculated for each of the Sitka spruce volume sample trees using the step 2, method 4 abbreviated tariff procedure.

Unfortunately, the 2008 assessment did not differentiate between European, Japanese and hybrid larch. Although hybrid and Japanese larch have similar growth and volume characteristics, European larch differs (Matthews and Mackie, 2006). As a result of this a tariff number was calculated for European larch and a separate tariff number calculated for hybrid/Japanese larch to see if they differed. In order to do this it was necessary to sample the height and DBH of each species separately.

In order to calculate the volume of each tree the following equation was used:

$$\text{Volume} = x + (y*BA) \qquad \text{(equation 5)}$$

Where $x = (0.036541*T) - (y*0.118288)$

$y = 0.315049301*(T-0.138763302)$

T = Tariff number

BA = Basal area (m^2).

This equation underpins the tariff tables and stand tariff number charts in Matthews and Mackie (2006).

3.2.3 Data analysis

Local volume table

The volumes calculated using Smalian's, Huber's and Newton's formulas were plotted against basal area. Linear regressions were then fitted using Genstat 11 (VSN International Ltd. Hemel Hempstead, UK) and the percentage of variance explained was compared. The equation resulting in the highest percentage of variance explained was then used in the production of the local volume table (Table 3.2). Basal area, rather than DBH, was used as there is generally a linear relationship (tariff line) between volume and basal area (Matthews and Mackie, 2006).

Table 3.3 Volume estimates for Sitka spruce volume sample trees using Smalian's, Huber's and Newton's equations. The number of trees, mean DBH and mean height of each size class are also shown.

Sitka spruce	**No. of trees sampled**	**Mean DBH (cm)**	**Mean Height (m)**	**Method of volume estimation**					
				Smalian's formula		**Huber's formula**		**Newton's formula**	
				Volume (m^3)	**% var.**	**Volume (m^3)**	**% var.**	**Volume (m^3)**	**% var.**
Small	15	18.93	13.54	0.16		0.16		0.16	
Medium	15	32.69	18.96	0.61		0.61		0.61	
Large	15	50.91	22.85	1.52	87.2	1.49	86.2	1.51	86.3
Extra large	8	73.61	26.75	3.46		3.39		3.42	

A total of 53 trees were measured, of which 39 were used for calibration and 14 were used for validation (Philip, 1994). These trees were felled at the same time to make the operation logistically viable. Those trees that were used for validation were selected randomly from the small, medium, large and extra large diameter classes. Within each diameter class each tree was assigned a unique number and then a subset of each diameter class were chosen using a random integer set generator (www.random.org was used for the random sampling). Four trees were selected from the small, medium and large diameter classes and two from the extra large diameter class.

Using regression analysis a relationship was established for both the calibration and validation data sets (Table 3.4). In order to assess whether the calibration regression and the validation regression differ significantly, a comparison of regression lines was carried out using a sequential analysis of variance (ANOVA) which shows the explanatory terms which shows which explanatory terms are necessary to describe the data. For example, the data (both calibration and validation) may be best described by a single regression line, two separate lines of the same slope or two lines with a differing slope (Chatfield *et al.*, 2009).

Table 3.4 The sequential analysis of variance for basal area (BA), the calibration (Ca) & validation (Va) data sets and their interaction.

	Degrees of freedom	**Sum of Squares**	**Mean Squares**	**Variance ratio**	**F probability**
BA	1	73.3	73.3	353.0	<0.001
Ca vs. Va	1	0.2	0.2	1.2	0.285
Ca vs. Va * BA	1	0.1	0.1	0.7	0.420
Residual	49	10.2	0.2	-	-
Total	52	83.8	1.6	-	-

Comparison of methods to predict volume

To examine the differences in volume prediction between the local volume table and single tree tariff numbers, the volume of each of the Sitka spruce volume sample trees was assessed using both methods. The regression coefficients from the local volume equation were not significantly different from those of the volume equation derived from the tariff tables (Draper and Smith, 1966). The analysis was carried out using Genstat 11 (VSN International Ltd. Hemel Hempstead, UK).

3.2.4 Calculating the EGS

The EGS for each of the six Blocks and the whole Trial Area were calculated using the following method:

- The diameter data for the Trial Area were taken from the 1990 and 2008 plot assessments (Mackintosh *et al.*, 2011)
- The volume of each tree was estimated using either the local volume table or a tariff number, depending on species (Table 3.1). At this stage the current growing stock was calculated.
- The volume contained within each diameter class was calculated by totalling the volume of each tree falling within the following classes: small (16-32 cm), medium (33-52 cm) and large (>52 cm). These classes are chosen based on those used in continental Europe (Schutz, 2001a) and differ from those used in the calculation of the Sitka spruce local volume table.
- The percentage volume in each size category was calculated.

3.3 Results

3.3.1 Local volume table for Sitka spruce

The volume estimates used in creating the local volume table were calculated using Smalian's formula as it had the highest percentage of explained variance, although the differences in volume estimation between all three formulas were small (Table 3.2).

The regression analysis of the calibration and validation data sets produced percentage variances of 82.2 % and 98.1% respectively. However, the sequential analysis of variance (ANOVA) (Table 3.4) indicates that the validation and calibration data do not differ significantly and can be described with one regression line as only basal area is significant ($p = <0.001$) (Figure 3.2).

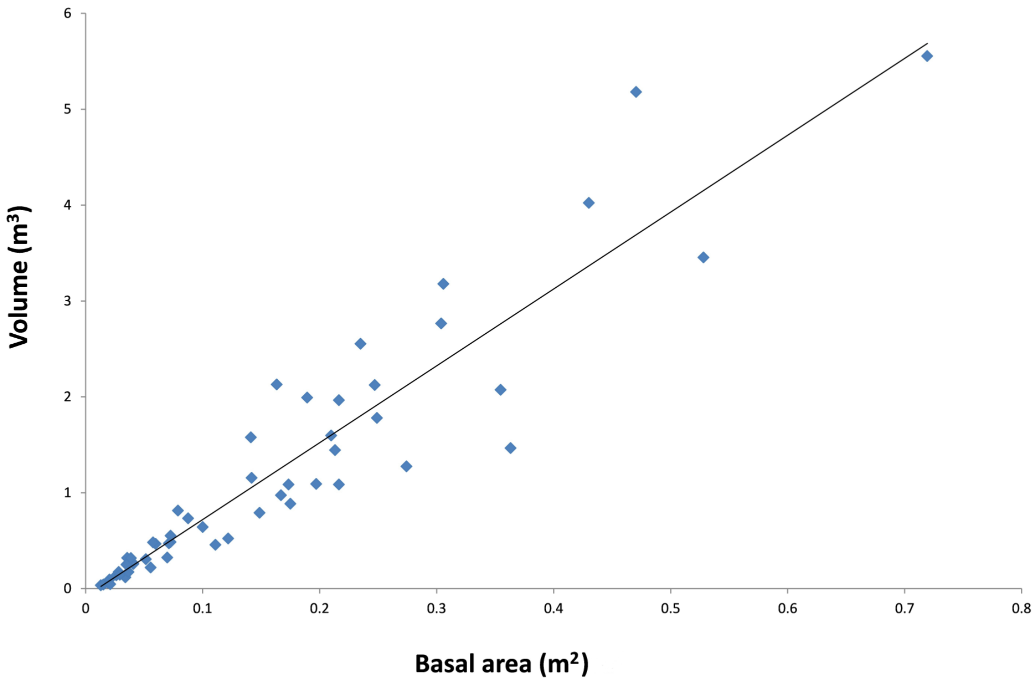


Figure 3.2 The relationship between basal area and volume for the Sitka spruce sample trees, showing a fitted linear regression.

A volume equation was produced for Sitka spruce:

$$\text{Volume} = 8.017*\text{basal area} - 0.0801 \qquad \text{(equation 6)}$$

Volumes were calculated for every diameter class throughout the range covered by the sample trees using equation 6.

3.3.2 Tariff numbers

The estimated tariff numbers for each species are shown in Table 3.3. The tariff number for Sitka spruce was 26 and that for European larch, Japanese larch and Scots pine was all 28; the value for Douglas-fir was 31.

3.3.3 Comparison of methods to predict volume

When volumes are estimated using an abbreviated tariff method as described by Matthews and Mackie (2006) the expected level of confidence is between ±12% and ±20%. Figure 3.3 shows these confidence intervals and the volume-basal area relationship for the local volume table. As the local volume table volume estimates fall within these confidence intervals it further indicates that the methods of volume estimation do not differ significantly.

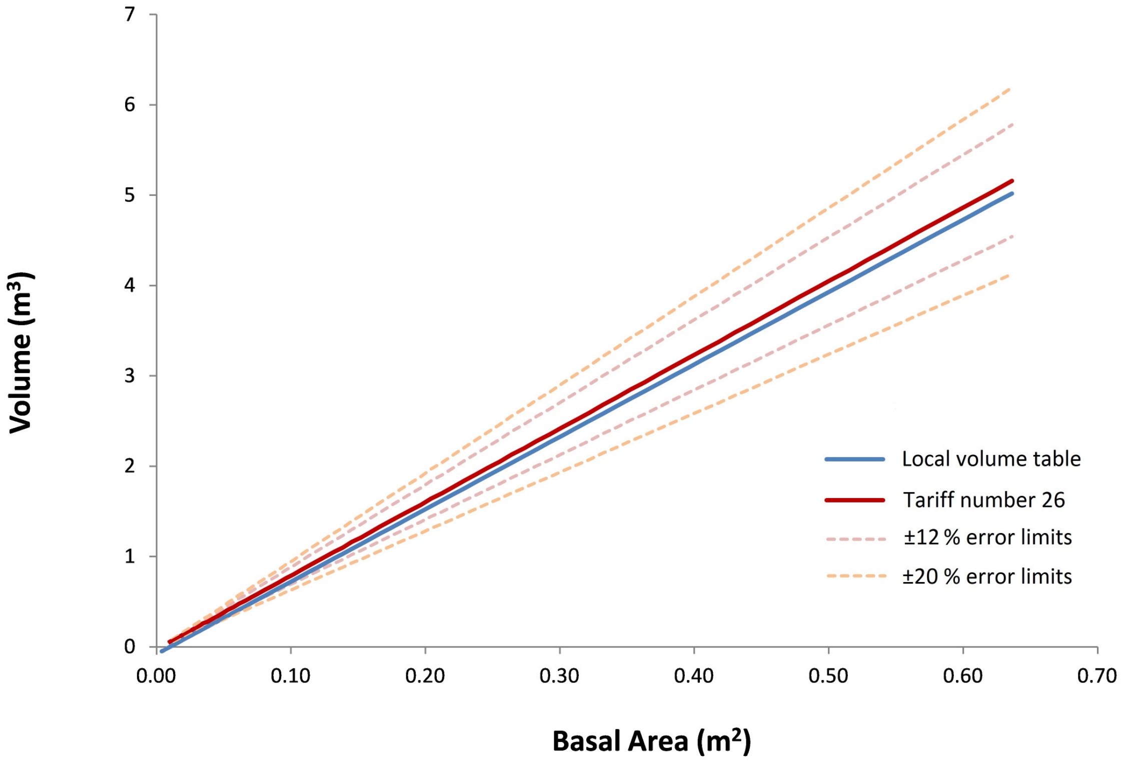


Figure 3.3 Sitka spruce local volume table and tariff number 26 volume estimates with ± 12% and ± 20 % error limits.

3.3.4 The EGS analysis

There has been a small overall increase in the volume per hectare between 1990 and 2008 though there have been both increases and decreases at the Block scale (Table 3.5). The number of trees per hectare (greater than 16 cm DBH) has decreased, though this varies at the Block scale.

Table 3.2 The basal area, standing volume and stocking density for the Trial Area and component Blocks in 1990 and 2008. Note the BA figures differ from those in Chapter 2 as the EGS only considers trees > 16cm DBH.

	Block A		**Block B**		**Block C**		**Block D**		**Block E**		**Block F**		**Trial Area**	
	1990	2008	1990	2008	1990	2008	1990	2008	1990	2008	1990	2008	1990	2008
BA (m^2 ha^{-1})	19.7	22.6	20.2	20.2	21.5	23.7	25.7	21.2	20.0	24.1	26.8	25.3	22.1	22.9
Volume (m^3 ha^{-1})	169	182	167	163	145	167	173	152	148	182	193	192	167	174
Trees ha^{-1}	289	291	317	191	556	412	508	345	263	338	354	314	345	318

The general trends in volume distribution are a decrease in the small diameter class from 49% to 40% and an increase in the large diameter class from 8% to 19% (Figure 3.4).

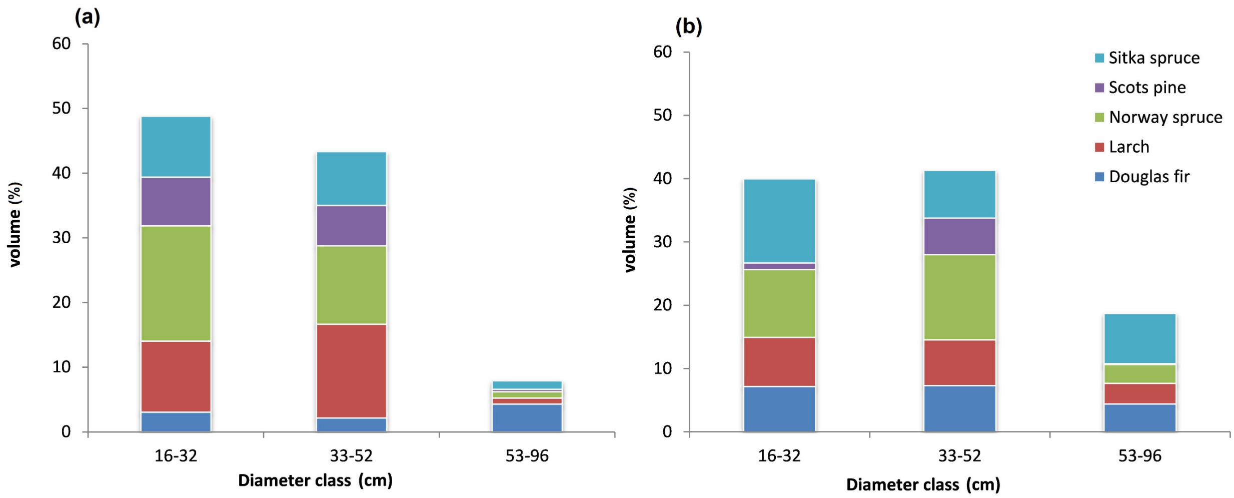
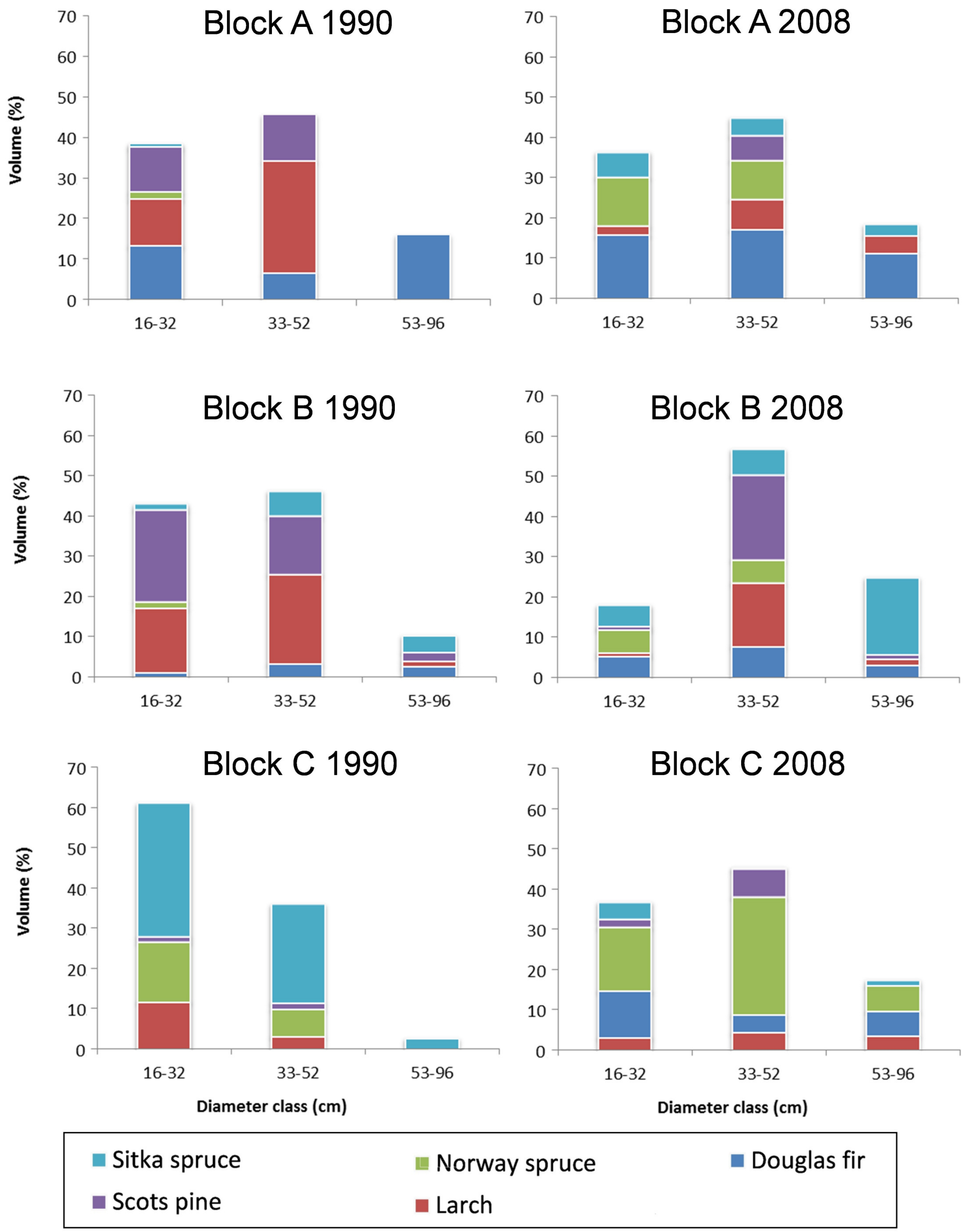


Figure 3.4 The volume distribution, showing species group composition for three diameter classes, for the Trial Area in (a) 1990 and (b) 2008.

There are some clear trends in species composition at the Trial Area scale between the 1990 and 2008 assessments (Figure 3.4). Douglas-fir is the only species to have increased in volume in all three diameter classes. Conversely, Scots pine has decreased in all three diameter classes. Larch has decreased in the small and medium diameter classes but increased in the largest diameter class. Norway spruce has shown a decline in the small diameter class but small increases in the medium and large classes. Lastly, Sitka spruce has increased its overall share of volume, particularly in the small and large diameter classes, but has decreased slightly in the medium diameter class. For a more detailed analysis of species composition in the Trial Area see Mackintosh *et al.*(2011).


Block A 1990
Block A 2008
Block B 1990
Block B 2008
Block C 1990
Block C 2008
Volume (%)
Diameter class (cm)
16-32
33-52
53-96
0
10
20
30
40
50
60
70
Sitka spruce
Norway spruce
Douglas fir
Scots pine
Larch

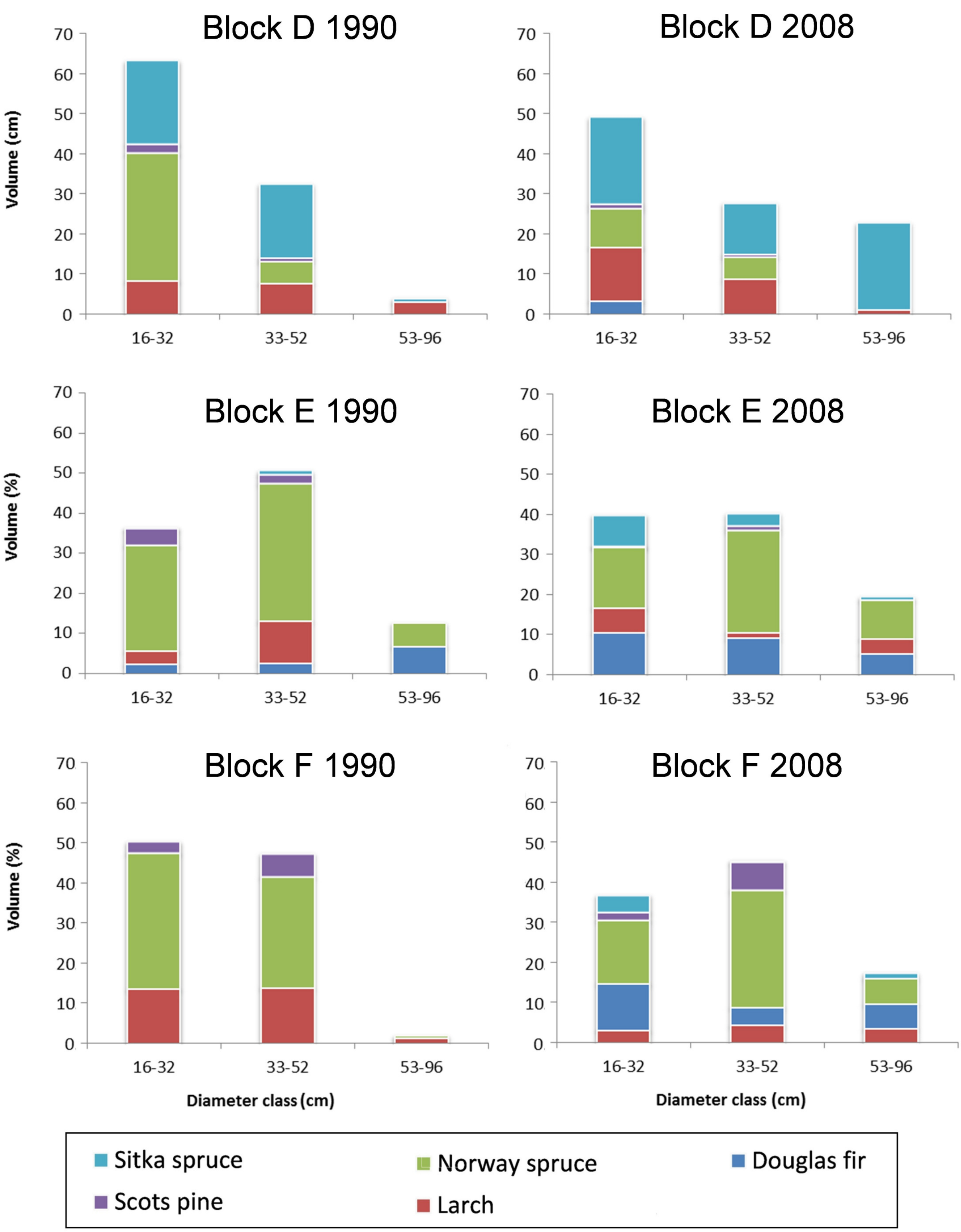


Figure 3.5 The volume distribution showing species composition for three diameter classes for each Block in 1990 (left of figure) and 2008 (right of figure).

For volume distribution, Blocks A, E and F follow the general pattern of the Trial Area in 2008 but there are some notable differences in the other three Blocks (Figure 3.5). In Block B there is a large decrease in the small diameter class and increases in both the medium and large size classes. Block C follows the general trend of the Trial Area but had much higher volumes in the small diameter class in 1990. Block D also has a much higher volume than the Trial Area in the small diameter class in 1990. However by 2008 the volume of the small diameter class has decreased where as the large diameter class has increased.

3.4 Discussion

3.4.1 The EGS analysis

There are very few examples of the EGS in the UK with which comparisons can be made. Those figures available, are either general proposals for the implementation of irregular forest management (Paterson, 1958) or deal with stands that are still undergoing transformation (Poore, 2007; Poore and Kerr, 2009b) (Table 3.6). The target volume distribution chosen by both Paterson (1958) and Poore (2007) fall within the broad targets outlined by Schutz (2001a). It is desirable to make comparisons with forests of similar species compositions and climatic conditions but due to a lack of EGS studies in the UK it is necessary to make comparisons with Continental Europe. However, even in Europe there is variation in the volume distribution between diameter classes. For instance, Boncina *et al.* (2002) looked at several different sites, mainly Silver fir–Beech (*Fagus sylvatica* L.) or Silver fir - Norway spruce selection forests. They used the same diameter classes as Schutz (2001a) but often record percentage volumes lower than the 15% lower boundary suggested in the small diameter class (Table 3.6). In addition, the medium and large size classes also have values that exceed the guidance values. It may be that the volume distributions found in the UK also fall outwith those outlined by Schutz (2001a).

Table 3.6 Volume distributions and growing stocks resulting from EGS analyses in the UK and Continental Europe.

Location	Growing stock (m^3 ha^{-1})	Size classes (%)		
		Small	Medium	Large
Glentress (1990)	167	48.8	43.3	7.9
Glentress (2008)	174	40.0	41.3	18.7
Stourhead (Shade tolerant)	*	20.0	35.0	45.0
Stourhead (Larch dominated)	*	30.0	40.0	30.0
Paterson – Moderate fertility	312	32.0	50.0	18.0
Paterson – High fertility	365	30.0	50.0	20.0
Switzerland (Jura) (Schutz, 1997)	350 -500	20.0	30.0	50.0
Serbia (Medarevic *et al.*, 2010)	498	15.0	35.0	50.0
Slovenia (Boncina *et al.*, 2002)	501	13.4	37.9	48.7
Slovenia (Boncina *et al.*, 2002)	340	12.6	52.4	35.0

*Standing volume was not given for the target EGS at Stourhead. However, the standing volumes of the three stands in 2006 ranged between 215 and 330 m^3 ha^{-1}.

Both the volume of the growing stock and the volume distribution measured in the Trial Area differ from common target distributions found in continental Europe. The standing volumes for all the Blocks and the Trial Area as a whole are low when compared to selection stands in central Europe (Boncina *et al.*, 2002; Schutz, 2002b). All the standing volumes were less than 200 m^3 ha^{-1} in the Trial Area whereas standing volumes in typical continental fir-spruce forests are in the range of 350-500 m^3 ha^{-1} (Schutz, 2002b; Medarevic *et al.*, 2010). Whilst the standing volume figures for Stourhead, an area of CCF forestry in England, are lower than many of those found in Europe, they are still higher than any of those found in Glentress (Table 3.6). Schutz (2002b) states that overshadowing occurs at basal areas higher than 27 to 33 m^2 ha^{-1} which can lead to poor volume increment and problems with recruitment. In the UK where there are relatively few shade tolerant conifer species it may prove difficult to maintain the balance between keeping a standing volume similar to those of continental Europe and facilitating recruitment.

One of the most important changes in the volume distribution of the EGS of the Trial Area is the increase in percentage volume contained in the large size class, coupled with a decrease in the small size class. Schutz (2001a), as summarised by Medarevic *et al.* (2010) has proposed that selection forests should have 15 to 34 % volume in the small class (up to 30 cm), 22 to 42 % in the medium class (31 to 50 cm) and 24 to 57 % in the large diameter class (>50 cm). At Glentress the medium class just falls within the aforementioned target but there is still too much volume in the small category and not enough in the large category. In order to establish whether the stand has reached an equilibrium state, it must first be demonstrated that standing volume remains constant through time i.e. that the volume removed is equal to the observed periodic volume increment. At present this is not possible in the Trial Area and will require further assessments (Boncina *et al.*, 2002; O'Hara and Gersonde, 2004; Schutz, 2006).

3.4.2 Volume prediction in irregular stands

The second objective of the study concerned volume prediction for the main species in the Trial Area. For Sitka spruce this took the form of a local volume table. The local volume table predicted volume accurately though predictions did not differ significantly, in statistical terms, from standard GB volume estimation methods (Matthews and Mackie, 2006). As a result the Trial Area can utilise the established tariff tables and it can not be concluded there are differences in basal area-volume relationships in CCF compared to even-aged silvicultural systems. However, the Trial Area is not fully transformed and many of the older trees have grown under even-aged conditions prior to 1952. In fully transformed CCF stands it is possible there would be a different basal area-volume relationship as growing conditions would be very different. Several factors can affect the allocation of biomass when a tree is growing. These include stress factors such as drought, nutrient imbalance and shade. In general, decreased light levels result in reduced root growth and stem taper, whereas water and nutrient stress result in increased root growth and stem taper (Waring, 1987). These differences in moisture, nutrient balance and light levels are mainly due to different types of competition. The level of this competition can be modified by management interventions such as thinning including the intensity and the interval between thinning (Moschler *et al.*, 1989; Pape, 1999; Peltola *et al.*, 2007; Ikonen *et al.*, 2008) all of which vary between even-aged and CCF management. There are also differences in the way different species react to competition (Jack and Long, 1991). For instance, Nilsson and Gemmel (1993) found that competition affected the diameter of Scots pine but not height, whereas in Norway spruce height and diameter were affected. One of the main resources that Sitka spruce, the dominant species in the Trial Area, competes for is light (Cannell and Rothery, 1984) with the amount of light a tree receives modifying the distribution of biomass along the stem (Nilsson and Gemmel, 1993). The above may result in the calculation of different tariff numbers than would be found in even-aged stands. One problem with the tariff tables is that the tariff lines are linear models. In reality the relationship between basal area and volume is not completely linear; the relationship is sigmoid. As a result the linear tariff lines underestimate the volume of trees with low basal areas (Brister and Lauer, 1985; Philip, 1994) and overestimate volume in trees with high basal areas (Philip, 1994). CCF, as opposed to clearfell-replant stands, has a much wider range of diameters (Knuchel, 1953; Smith, 1986) and thus an alternative basal area-volume relationship may be more suitable such as a polynomial relationship of volume on increasing powers of diameter (Philip, 1994).

3.4.3 Implications for management

Due to a lack of UK examples it is necessary to utilise target volume distributions from continental Europe. For the effective use of EGS as a guide to management in the UK it is imperative that equilibrium states for different species and species mixtures are established. Schutz (2006) states that an understanding of recruitment, removal and movement through the diameter classes is essential in order to establish an equilibrium state. In theory the volume removed during thinning should equal the volume increment. In the Trial Area it initially appears that there is too much volume in the smallest diameter class. However, care should be taken before intervening to reduce the number of small trees as the overall growing stock is low relative to other stands in the UK (Poore and Kerr, 2009b) and continental Europe (Zingg *et al.*, 1997; Schutz, 2002b). Furthermore, necessary recruitment into the medium diameter class should be considered along with causes of mortality in seedlings and saplings which in this case probably results from browsing by deer (Kerr and Mackintosh, 2010; Kerr and Mackintosh, 2012). A further complication is that more than one single equilibrium can be appropriate for multi-aged stands i.e. there will be more than one volume distribution that results in a sustainable yield (O'Hara *et al.*, 2007).

In central Europe a measure called 'passage á la futaie' is used to check whether sufficient trees are recruited into the smallest size class; about 1 m^2 per ha of new small trees in a 5 year period (Foret Privee Francaise., 2012). It could be argued that EGS analysis should include trees smaller than 16 cm (the lower limit commonly used in continental Europe) to gain a better understanding of the growth and recruitment of small trees. This study only includes trees greater than 16 cm DBH but utilises a dataset that includes trees down to 7 cm DBH and as a result it was possible to analyse the volume and the number of trees contained in the 7 to 16 cm diameter class. The 7 to 16 cm diameter class contained only 2.8% of the volume in 1990, falling to 2.2% in 2008. However, the percentage number of trees was 48.8% in 1990, falling to 36.4% in 2008. The effort required to measure these extra trees for such a minor percentage volume justifies using 16cm as a lower limit when carrying out EGS analysis.

The results show certain areas of the Trial Area are moving towards an equilibrium state relative to the volume distribution outlined by Schutz (2001a), whilst others require further management. This is supported by concurrent work that looked at reverse-J distributions at various spatial scales within the Trial Area (Mackintosh *et al.*, 2011). As of 2010 a new management plan for the Trial Area was initiated (Kerr *et al.*, 2010b) which set out objectives to manage areas that had been previously neglected. The shift in volume distribution between the small and large diameter classes has resulted in a move towards EGS distributions from the UK (Paterson, 1958; Poore, 2007; Poore and Kerr, 2009b) and Continental Europe (Schutz, 2001a; Boncina *et al.*, 2002; Medarevic *et al.*, 2010). As more volume is required in the largest diameter class, management should avoid felling many large trees. However, trees should not be left to grow to sizes that make harvesting and processing unfeasible. In the case of Glentress, this limit is around 70 cm DBH (Tracey, 2011). As previously stated there are no UK forest stands that are fully transformed and have used EGS. Therefore the desirable volume distribution for upland, coniferous woodland may differ significantly from those in the literature. Only through continued periodic assessment of the Trial Area will reliable targets structures be attained.

The reduced percentage volume of larch and pine in the small diameter class will result in fewer trees of these species being recruited into the larger diameter classes. Coupled with an increase in Sitka spruce in the small diameter class the result is likely to be a forest increasingly dominated by Sitka spruce.

3.4.4 Comparison of the EGS and reverse-J curves

The EGS and the reverse-J curves are similar methods of informing management in many respects. The fundamental differences are that the former utilises three large diameter classes as opposed to many smaller classes (typically 5 cm) and the EGS looks at the distribution of volume rather than number of trees to the diameter classes. The lack of information on trees below 16 cm DBH in the EGS means that it does not consider regeneration. This is especially important in the UK as there are many problems with regeneration to contend with such as browsing pressure, competition and lack of good quality parent crops (Hart, 1991). In principle the EGS could include smaller diameter classes, similar to those used in reverse-J analysis, and could set a lower diameter limit of 7 cm. However, as the majority of other studies use a 16 cm lowest diameter it could cause problems when making comparisons. The EGS could be carried out using basal area rather than volume. Calculating basal area from DBH is a simple practice (Matthews and Mackie, 2006) and would avoid the problems involved with volume estimation explored in this paper.

3.5 Conclusion

Both the standing volume and volume distribution of the Trial Area have shown changes between 1990 and 2008. The standing volume has increased but is still much lower than values from related literature for both the UK and continental Europe. The percentage volume distribution is nearer published values, with a decrease in volume in the small diameter class and an increase in the large between 1990 and 2008. The changes in species composition indicate a decrease in Scots pine and larch coupled with an increase in Sitka spruce. Interpretation of the EGS should be carried out in conjunction with knowledge of recruitment into the smaller size classes of trees (below 16cm DBH) and the maximum DBH local saw-mills will accept. In order to establish the equilibrium state for the Trial Area it is essential that further stand assessments are carried out until the volume distribution becomes stable. Only at this point can a suitable example EGS target structure be set for upland, coniferous woodlands in the UK.

A local volume table was successfully created for Sitka spruce in the Trial Area. However, its estimates do not differ significantly from established tariff relationships. Despite this, stem biomass allocation may be different in fully transformed CCF stands as they provide a different light environment. Therefore a local volume table should be considered if carrying out EGS.

There are options for EGS analysis worthy of investigation, such as changing the diameter range to include smaller trees or using basal area in place of volume, which may improve its usefulness to management. However, the current reverse-J method provides output that is more easily attained and understood by forest managers.

3.6 Acknowledgements

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Chapter 4

The physiological response of Sitka spruce seedlings grown in Continuous Cover Forestry

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Abstract

The increasing adoption of Continuous Cover Forestry (CCF) management requires an improved understanding of natural regeneration and its relationship to light. This study utilised morphological and ecophysical measurements of chlorophyll fluorescence and gas-exchange to assess Sitka spruce seedlings growing under differing canopy conditions in the Glentress CCF Trial Area. Open (15-35 $m^2 ha^{-1}$) and closed (>35$m^2 ha^{-1}$) canopy areas were selected and plots established. Statistically significant differences were found in the physical characteristics of the seedlings grown in the open and closed plots with leaf area and needle mass being much lower in the closed plots. The mean Apical Dominance Ratio (ADR) was 1.41 for the open plots and 0.9 for the closed plots which is consistent with previous studies suggesting an ADR greater than one is necessary for successful regeneration. ADR could be used as a useful indicator of when thinning interventions are required in Sitka spruce CCF stands.

Ecophysiological assessment showed electron transfer rate (ETR) had a linear relationship with PAR though ETR was higher in closed than open plots for a given value of PAR. However, there are very few values of ETR greater than 50 $\mu mol\ m^{-2} s^{-1}$ in the closed plots. The results of the gas-exchange measurements showed that in the open plots photosynthetic assimilation rates (A) increased with PAR. However, there was no obvious relationship in the closed plots. The linear relationship between A and ETR, which has been observed under controlled conditions, was not reproduced under field conditions. This may result from fluctuation of environmental variables and chlorophyll fluorescence and A not being measured simultaneously.

4.1 Introduction

CCF has increased in popularity since the early 1990s as a means of developing multi-layered stand structures and as a result of policy drivers promoting low impact sustainable systems (Scottish Executive, 2006; Forestry Commission, 2009; Forestry Commission., 2011b). There are many definitions of CCF but for the purposes of this study those outlined in the UK Forest Standard are used. CCF is defined as an approach to management "whereby the forest canopy is maintained at one or more levels without clearfelling" where a clearfell is defined as any felled area greater than 0.25 hectares (Forestry Commission., 2011b). In addition, CCF is also commonly recognised to favour species diversity and natural regeneration (Mason *et al.*, 1999). CCF's increasing popularity started in the late 1980s, with Pro Silva Europe forming in 1989 as an association of foresters who employed forest management which emulated natural processes. The UK based Continuous Cover Forestry Group (CCFG) formed shortly after this in 1991 with the aim of transforming even-aged plantations into structurally, visually and biologically diverse forests (CCFG, 2011). The social, cultural and ecological importance of forestry was further emphasized at the 1992 "earth summit" in Rio, the 1993 Helsinki guidelines and The Lisbon Declaration in 1998 (Warren, 2002). The UK Forestry Standard promotes the use of low impact methods such as CCF, especially in semi-natural woodlands (Forestry Commission., 2004) and this is echoed in the Scottish Forestry Strategy which states "low impact systems are currently under-represented in Scotland and a strategic aim of this Strategy is to increase their coverage"(Scottish Executive, 2006). The National Assembly for Wales' policy is to adopt alternative management systems to clearfelling where they would make a better contribution to ecosystem services (Forestry Commission, 2009). The promotion of CCF through these policy documents is a result of perceived benefits such as aesthetics (Ribe, 1989), increased *in situ* carbon storage (Seidl *et al.*, 2007; Seidl *et al.*, 2008; Stokes and Kerr, 2009), resilience to climate change and pest species (Mason, 2007) and increased biodiversity (Bengtsson *et al.*, 2000; Michelsen, 2008).

Sitka spruce (*Picea sitchensis* (Bong.) Carr.), the main commercial conifer species grown in the UK, accounted for 32 percent of the UK's forest cover in 2011 (Forestry Commission., 2011a). As a result, any implementation of the policies outlined will involve the transformation of existing even-aged Sitka spruce plantations to CCF systems. Therefore, as CCF systems favour natural regeneration, an understanding of Sitka spruce regeneration and seedling physiology is essential to successful management. Sitka spruce is not a shade tolerant species and is usually described as being an intermediate shade bearer (Mason *et al.*, 1999) or a light demander (Hart, 1991). However, what constitutes an acceptable below-canopy level of light is less well defined. Hale (2004) suggests critical basal areas for several species to achieve 50 percent of the growth that would be achieved in full light with the threshold basal area for Sitka spruce being 30 m^2 ha^{-1}. Page *et al.* (2001) also suggest a figure of 30 m^2 ha^{-1} for successful advanced regeneration of Sitka spruce. However, despite there being a good relationship between basal area and canopy transmittance for continuous, homogenous canopies, this relationship breaks down when there are gaps in the canopy (Hale, 2003). As a result of management interventions, CCF canopies are likely to be discontinuous containing many small gaps. The regeneration itself is most likely to occur in gaps though seedlings will establish beneath the canopy if canopy openness is sufficient (Gray and Spies, 1996).

Underlying ecophysical principles governing seedling development

In CCF, below canopy light-levels will be lower due to attenuation of light when passing through canopy (Duncan, 1971; Nobel *et al.*, 1993). At lower light levels there is a straight line relationship between photosynthetically active radiation (PAR) and net photosynthesis (A, μmol CO2 m^2 s^{-1}) (Harbinson *et al.*, 1990; Salisbury and Ross, 1992) and electron transfer rate (ETR) (Bertin *et al.*, 2009b). As a result it is possible to establish a straight-line relationship between A and ETR (Tsuyama *et al.*, 2003). However, this relationship can break down at high and very low levels of light (Oquist and Chow, 1992; Tsuyama *et al.*, 2003) though high light levels are unlikely to occur beneath an existing canopy. If it is possible to estimate A from ETR measurements this would aid future seedling physiology studies as a chlorophyll fluorometer could be used independently of a gas exchange analyser. The main benefits of this are that chlorophyll fluorometers are lighter, cheaper, less technically complex and have shorter sampling times than a gas-exchange analyser.

The Glentress Trial Area, one of the longest running CCF experimental trials in the world (Kerr *et al.*, 2010a), presents a unique opportunity to investigate Sitka spruce regeneration. The Trial Area was established in 1952 by Professor Mark Anderson, who was then head of the forestry department at the University of Edinburgh. An agreement between the University and the Forestry Commission resulted in the establishment of a 117 hectare trial area to investigate the transformation from an even-aged to a CCF system. The overall aim of the Trial Area was to transform from even-aged stands to an irregular structure using a group selection system over a 60 year transformation period. The transformation involved felling two hectares, comprising of multiple group selections between 0.1 and 0.2 hectares in size, in consecutive years. Therefore over a 60 year period, the entire Trial Area would be felled with the regenerating groups being at varying stages of development. A full account of the 1952 to 1990 period is given in Kerr *et al.* (2010a).

The objectives of this study were to:

1. To establish the differences in seedling architecture of Sitka spruce growing under different canopy conditions.

2. To assess the utility of chlorophyll fluorescence measurements taken under ambient light conditions in developing an integrated measure of site suitability for seedling growth.

3. To assess whether ambient measurements of chlorophyll fluorescence can be used to estimate seedling photosynthesis.

4.2 Methods

4.2.1 Site description

Glentress forest is situated 25 miles south of Edinburgh, approximately two miles east of Peebles (Longitudinal 3^{o} 9' W, Latitudinal 55^{o} 40' N). Its total area is 1140 ha of which the CCF trial area makes up 117 ha (Figure 1). The Trial Area spans an altitudinal range of 240 to 560 metres. The Glentress burn runs approximately north to south, flowing through Blocks C, D and E with its catchment including areas of every Block. The soil types, derived from Ordovician sediments, can be categorised depending on the topography. On the lower slopes there are well drained acid brown earths whereas podzolic peaty surface-water gleys, often with iron pans, occupy the upper slopes (Kennedy, 2002). The general aspect of the Trial Area is southerly with an annual precipitation between 1000 and 1500 mm (Wilson *et al.*, 1999; Kerr *et al.*, 2010a). The main overstorey species are Sitka spruce, Norway spruce (*Picea abies* L.), Douglas fir (*Pseudotsuga menziesii* (Mirb.) Franco), Japanese larch (*Larix kaempferi* (Lamb.) Carr.) and Scots pine (*Pinus sylvestris* L.). In addition to these there are several other conifer and deciduous species. On the upper slopes, the ground vegetation is dominated by grass heath, the main component being wavy hair grass (*Dechampsia flexuosa* (L.) Trin.) with heather (*Calluna Vulgaris* (L.) Hull) appearing in patches. The lower and mid slopes are characterised by bracken (*Pteridium aquilinum* (L.) Kuhn), Ferns (*Dryopteris* spp.) and creeping soft grass (*Holcus mollis* L.) (Wilson *et al.*, 1999; Kerr *et al.*, 2010a). All the plots used in this study were located in Blocks C and D (Figure 4.1) with an overstorey almost exclusively of Sitka spruce.

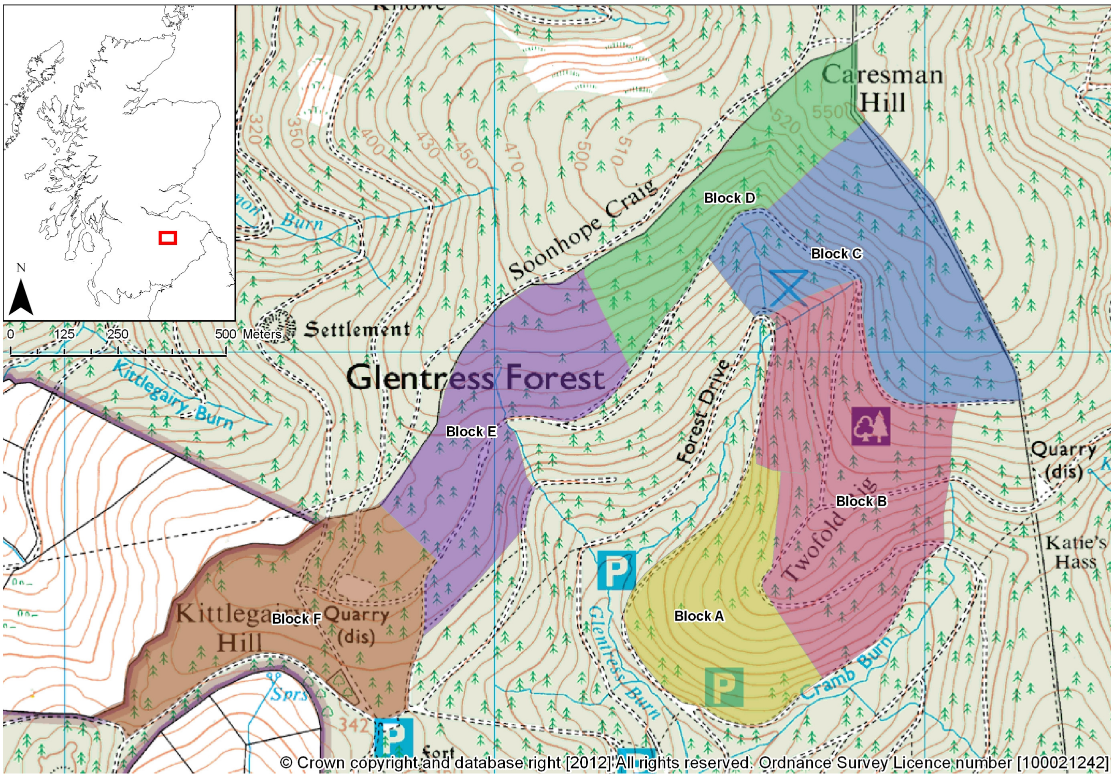

Figure 4.1 Map of the Glentress Trial Area showing Blocks A-F.

4.2.2 Experimental design

Plots were established in areas categorised as open (15-35 $m^2 ha^{-1}$) or closed (>35 $m^2 ha^{-1}$) canopy. The locations for plot establishment were chosen based on data collected during a 2008 assessment. In 2008 210 permanent sample plots were surveyed as part of the monitoring of transformation to CCF. Each permanent sample plot is 10 by 40 metres and comprises of four 10 by 10 metre subplots. The number of Sitka spruce seedlings and basal area were recorded for each subplot. This information was used to select a preliminary list of open and closed plot locations. Thirty one subplots were selected based on basal area, presence of Sitka spruce seedlings and soil type. The selected plots were then assessed for suitability. Canopy-scope measurements, which indicate the amount of visible sky, and Sitka spruce seedling numbers were recorded (Hale and Brown, 2005). Based on the preliminary assessment eight subplots were chosen: Four open plots and four closed canopy plots. In each of these subplots a seedling physiology plot was then established. The centre of each subplot was located using a tape measure and compass and a circular plot of two metre radius was established. The centre of each plot was permanently marked with a cane, and the perimeter marked with spray paint. The basal area of the surrounding subplot was calculated using the DBH data recorded during the 2008 assessment. Hemispherical photographs were taken at the centre of each seedling physiology plot to establish the amount of visible sky. The hemispherical photographs were taken using a Nikon Coolpix 4500 digital camera (Nikon Imaging Japan Inc., Tokyo, Japan) on a self-levelling mount using the methodology set out by Hale (2005a).

4.2.3 Seedling physiology

Three aspects of seedling physiology were measured in each plot: physical characteristics, gas exchange and chlorophyll fluorescence. All measurements were recorded in each of the eight experimental plots. Chlorophyll fluorescence measurements were recorded during five days in 2009 and three days in 2010, gas exchange measurements were recorded during the three sampling days in 2010 and the physical measurements were taken at the end of the growing season in 2010.

The seedling physiology plots were located in blocks C and D of the Trial Area (Figure 4.1) with four plots in Block C and four in Block D. During a particular sampling day the plots were sampled in one Block. Each plot would be sampled consecutively and this would repeat during the course of the day.

Within each plot 10 seedlings were selected and marked for chlorophyll fluorescence measurements. All measurements were recorded using a portable pulse modulated fluorometer (MINI-PAM, Heinz Walz GmbH, Effeltrich, Germany) with a leaf-clip holder (part no. 2030-B) for data recorded under instantaneous, ambient conditions and dark leaf clips (part no. DLC-8) for dark adapted fluorescence measurements. All measurements were recorded from current year needles on the first whorl of the seedlings. Dark leaf clips were attached to branches and left for at least 30 minutes in order to allow dark adaptation to occur. Dark adapted fluorescence (Fm) and fluorescence under ambient light conditions (Fm') were recorded for each seedling in every plot. The ambient light was recorded by the PAR sensor on the MINI-PAM.

Three seedlings in every plot were marked and used for the gas exchange analysis. The same branch on each seedling was used for all measurements (new growth, first whorl), over all the sampling days, to maintain consistency and to ensure that leaf area was calculated correctly. All measurements were recorded using a portable photosynthesis system (LI-6400, LI-COR environmental GmbH, Bad Homburg, Germany). The first measurement of *A* was recorded after photosynthesis and conductance stabilised. The seedling was then dark adapted and a measurement of respiration was recorded. The seedling was then exposed to ambient conditions and a final measurement of *A* was taken. The initial values of *A* were based on standard leaf areas for conifer shoots programmed into the Li6400. To accurately calculate *A*, actual leaf areas were measured. At the end of the sampling period the sample shoots were removed and their leaf area calculated using a Li 3100C Area meter (LI-COR environmental GmbH, Bad Homburg, Germany). *A* was then recalculated using actual leaf area.

Physical measurements of all seedlings were recorded:

1/ Seedling height, measured from the root collar to the tip of the leader.
2/ Leader length, measured from the first whorl to the tip of the leader.
3/ Length of all branches on the first whorl.
4/ The root collar diameter, measured twice at 90^{o} angles.
5/ The dry mass of needles.
6/ Nitrogen and carbon content of needles.
7/ Leaf area of needles removed from branches used for gas exchange analysis.

Numbers one to three were measured using a tape measure. The root collar diameter was measured using a Vernier calliper. Two measurements were recorded at 90^{o} to each other and an average was taken to ensure asymmetric growth was accounted for. In order to measure the dry mass of the needles they were first removed from the branch and then dried at 80^{o}C for 24 hours. Their weight was then measured using a SC2 microbalance (Sartorius, Goettingen, Germany). To establish the nitrogen and carbon content of the needles they were first ground to powder using a Retsch ultra Xcentrifugal mill ZM100 (RETSCH GmbH, Haan, Germany). Approximately 5 mg of the powder, per sample, was weighed out and placed in aluminium foil sample-holders. The carbon and nitrogen percentage content was then measured using a Carlo Erba NA2500 elemental analyser (Carlo Erba Reagent, Milan, Italy). In addition to the measurements mentioned above, apical dominance ratio (ADR) was calculated by dividing leader length by lateral length (Grassi and Giannini, 2005) and the sturdiness quotient was calculated by dividing seedling height by root collar diameter (Menzies *et al.*, n.d.).

4.2.4 Data analysis

The hemispherical photographs were analysed using Hemiview canopy analysis software (Delta-T Services Ltd., Cambridge, England). A user defined threshold results in greyscale photographs being converted to black (canopy) and white (sky) pixels. The threshold can be altered which in turn results in a change in the classification of sky and canopy. By comparing the original picture and the classified image this process was continued until a decision was made on the best classification. When processing each image, it was important to orientate images so they were north aligned. The images were then randomized and the process repeated. An average of the two reading was then calculated (Hale, 2005b). Hemiview produces four outputs: Vissky, Indirect Site Factor (ISF), Direct Site factor (DSF) and Global Site factor (GSF). Vissky is a measure of the sky visible through the canopy, ISF is an indicator of indirect sunlight, DSF is an indicator of direct light and GSF is a weighted indicator of ISF and DSF based on the sun’s passage through the sky throughout the year.

Plot characteristics were checked against the initial plot categorisation of open and closed. The hemispherical photographs were taken at the end of the sampling period. Analysis of the photographs showed that one of the plots categorised as being closed should be recategorised as open. As a result the statistical analysis of the data utilised unbalanced statistical tests. All the seedling physiology data analysis was carried out using Genstat 11 (VSN International Ltd. Hemel Hempstead, UK) and Microsoft Excel (Microsoft, Redmond, Washington, USA). Means for the physical characteristics of the seedlings were calculated and are expressed with standard errors. Comparisons between the seedlings physical characteristics in the closed and open plots used unbalanced analysis of variance (ANOVA).

4.3 Results

4.3.1 Understory Light Environment

The light environment varied significantly between open and closed plots (Figure 4.2), though measurements in both light regimes were predominately located between 0 and 100 µmol m^{-2} s^{-1} (Figures 4.3a and b). Figure 4.2 shows the difference in PAR, as measured by the chlorophyll fluorometer, in open and closed plots during the 2009 and 2010 assessments. On all sampling days there was a clear difference in average PAR between the open and closed plots.

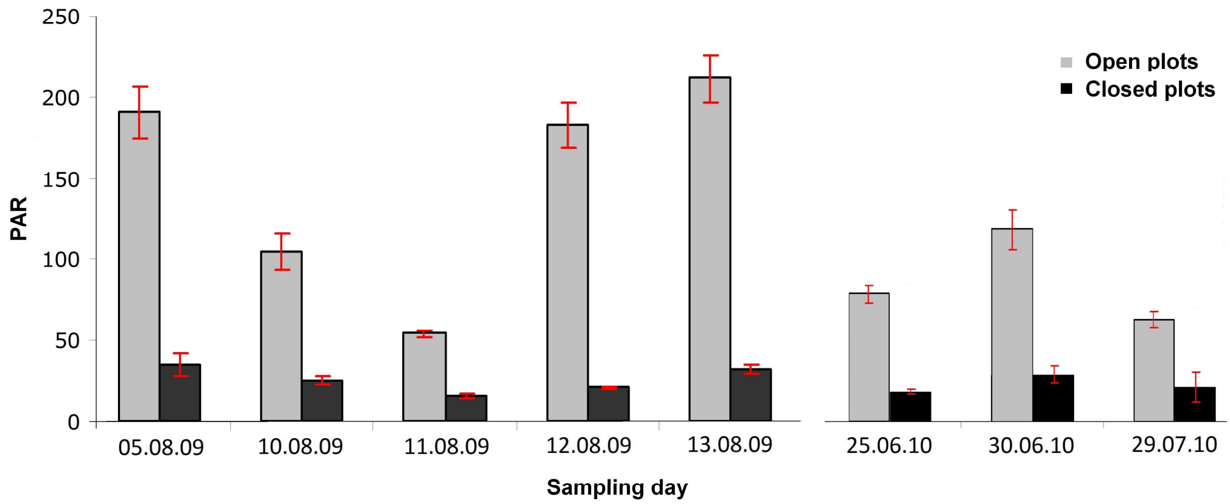

Figure 4.2 Average daily PAR measured in the open (grey) and closed (black) plots during the five sampling days in 2009 and three sampling days in 2010. Values are means ± one standard error.

In 2009 84% of the PAR measurements recorded from the closed plots were between 0 to 100 µmol m^{-2} s^{-1}(Figure 4.3a). In 2010 this figure had increased to 96.6%. For both the open and closed plots there were many more low PAR measurements than high PAR measurements (Figures 4.3a and b).

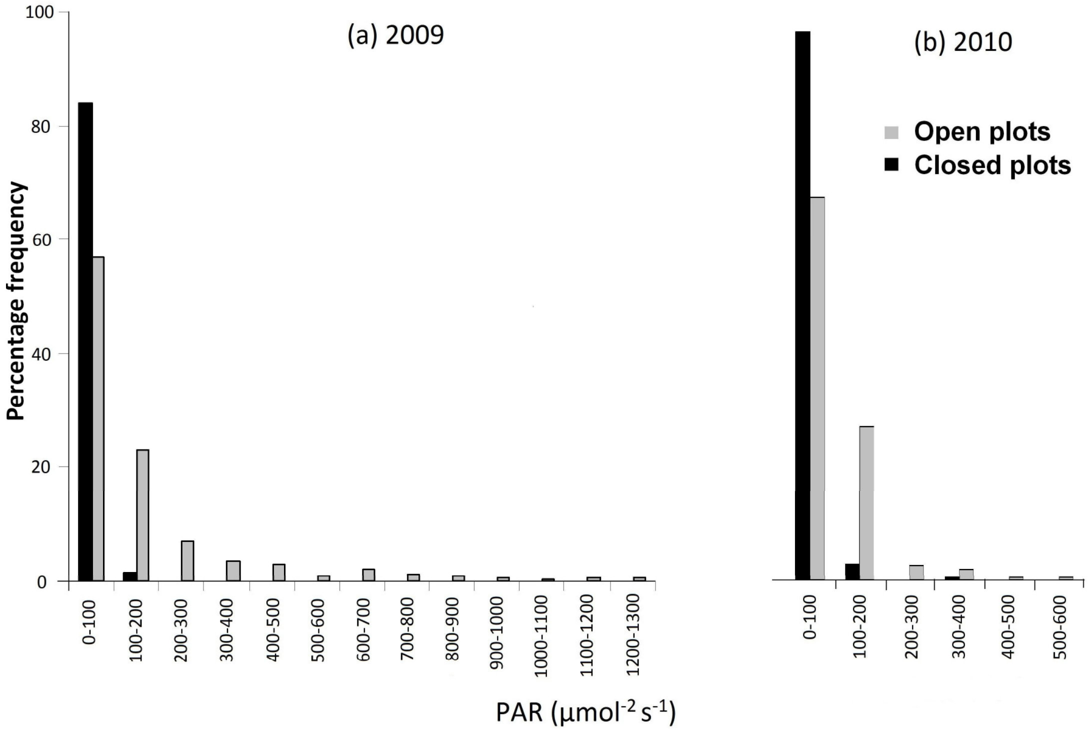

Figure 4.3 The percentage frequency of PAR measurements for open (grey) and closed (black) plots during the (a) 2009 and (b) 2010 measurement periods.

4.3.2 Canopy assessments

The open and closed plots show clear differences in canopy openness. All of the open plots have large portions of sky visible where as the closed plots exhibit fewer, smaller canopy openings (Figure 4.4).

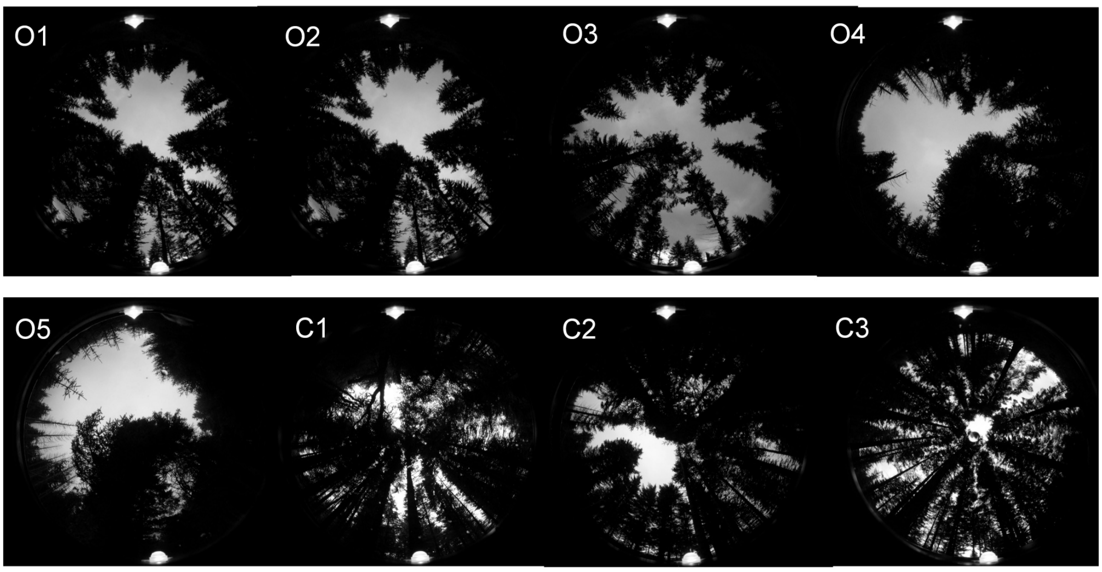

Figure 4.4 The hemispherical photographs for the open (O1-O5) and closed (C1-C3) plots used in the analysis of canopy openness.

Plot based assessments from the hemispherical photography analysis, basal area and canopy scope measurements are shown in Table 4.1. Analysis using unbalanced ANOVA found that there were statistical differences between the open and closed plots for basal area, canopy scope measurements and the hemispherical photography outputs. The one anomalous plot is O5 which has a high basal area but has a high proportion of Vissky and a large opening in the canopy (Figure 4.4).

Table 4.1 Output from the hemispherical photography analysis, basal area and canopy scope readings for the open and closed plots.

	Hemispherical data					Basal	Canopy
Plot	**VisSky***	**ISF***	**DSF***	**GSF***	**LAI***	**Area***	**Scope***
C1	0.08	0.11	0.17	0.13	2.79	69.47	5
C2	0.09	0.13	0.13	0.13	3.03	42.63	29
C3	0.10	0.11	0.10	0.11	2.30	41.20	4
Closed average	**0.09**	**0.12**	**0.13**	**0.12**	**2.71**	**51.10**	**12.7**
O1	0.15	0.21	0.29	0.24	2.56	28.46	47
O2	0.17	0.26	0.13	0.22	2.31	0	39
O3	0.26	0.35	0.37	0.36	1.39	24.12	72
O4	0.22	0.32	0.19	0.28	1.66	14.99	63
O5	0.23	0.30	0.42	0.34	1.37	44.72	56
Open average	**0.21**	**0.29**	**0.28**	**0.29**	**1.86**	**19.46**	**55.4**

*Open and Closed plots are significantly different at >95% level.

4.3.3 Seedling Physiology

There were clear differences in the physical characteristics of seedlings in open and closed plots (Table 4.2). Seedling height, root collar diameter, leader length, ADR and average lateral length were significantly different ($p < 0.001$). The average leader length in the open plots is over three times the length in closed plots and the average lateral length of the open plots is approximately double that of the closed plots. This resulted in an average ADR above one in all the open plots and below one in closed plots (though it is above one in plot C3). However, the sturdiness quotient does not differ significantly between open and closed plots.

Table 4.2 The arithmetic means of the physical measurements recorded from the seedlings in each plot with ± one SE.

Plot	**Height (cm) ***	**Root collar (cm)***	**Leader length (cm)***	**Avg. lateral length***	**ADR***	**Sturdiness quotient**
O1	30.44 ± 5.35	0.75 ± 0.14	10.36 ± 2.15	6.72 ± 1.17	1.54	40.59
O2	43.98 ± 7.56	0.76 ± 0.13	11.02 ± 1.97	8.24 ± 1.11	1.34	57.87
O3	38.48 ± 3.69	1.14 ± 0.32	13.81 ± 1.74	7.48 ± 1.38	1.84	33.75
O4	50.49 ± 4.89	1.47 ± 0.49	9.80 ± 1.25	8.29 ± 0.94	1.18	52.51
O5	59.72 ± 7.15	1.17 ± 0.19	10.98 ± 1.51	8.63 ± 0.73	1.27	51.04
Open average	**45.04 ± 2.86**	**1.06 ± 0.13**	**11.16 ± 0.76**	**7.93 ± 0.47**	**1.41**	**47.15**
C1	14.94 ± 0.70	0.30 ± 0.01	2.39 ± 0.33	3.03 ± 0.40	0.79	49.80
C2	17.28 ± 1.64	0.36 ± 0.03	2.13 ± 0.26	2.76 ± 0.27	0.77	48.00
C3	28.55 ±3.97	0.52 ± 0.05	6.33 ± 0.91	5.91 ± 0.84	1.07	54.90
Closed average	**20.25 ±1.75**	**0.39 ± 0.03**	**3.60 ± 0.50**	**3.93 ± 0.41**	**0.90**	**50.90**

*Open and Closed plots are significantly different at >95% level.

At the seedling branch scale, leaf area and branch foliar dry mass were significantly different ($p = 0.001$) (Table 4.3). The percentage carbon was significantly different ($p = 0.007$) but percentage nitrogen was only significant at 90% confidence.

Table 4.3 Characteristics of foliage from branches used for the gas-exchange measurements ± one standard error.

Plot	Leaf area*	Foliage dry mass (g)*	% N**	%C*
O1	13.83 ± 0.75	0.23 ± 0.04	1.45 ± 0.18	48.31 ± 0.15
O2	13.28 ± 3.47	0.23 ± 0.07	1.27 ± 0.15	48.02 ± 0.56
O3	16.10 ± 2.14	0.30 ± 0.02	1.89 ± 0.07	48.24 ± 0.36
O4	9.90 ± 2.48	0.17 ± 0.04	0.79 ± 0.06	48.32 ± 0.15
O5	10.02 ± 1.75	0.18 ± 0.03	0.85 ± 0.06	48.38 ± 0.45
Open average	**12.63 ± 1.08**	**0.22 ± 0.022**	**1.25 ± 0.12**	**48.25 ± 0.14**
C1	3.96 ± 0.26	0.05 ± 0.001	0.99 ± 0.06	47.29 ± 0.25
C2	6.97 ± 1.90	0.12 ± 0.03	0.75 ± 0.12	47.80 ± 0.07
C3	9.07 ± 0.76	0.14 ± 0.02	1.15 ± 0.13	47.76 ± 0.21
Closed average	**6.66 ± 0.95**	**0.10 ± 0.02**	**0.97 ± 0.08**	**47.62 ± 0.13**

*Open and Closed plots are significantly different at >95% level.
**Open and closed plots are significantly different at the >90% level.

It was expected that physical characteristics both at the seedling (Table 4.2) and branch scale (Table 4.3) would vary in relation to canopy openness and PAR levels (Figure 4.5). The PAR measurements used in figure 4.5 are an average for each of the gas-exchange seedlings measured during the sample days in 2010. However, when these relationships were explored there were no clear relationships other than those shown in Figure 4.5. Even with these relationships, the highest percentage variance described was only 29.5%, when both the open and closed plots were combined, for vissky versus specific leaf area (SLA, m^2 kg).

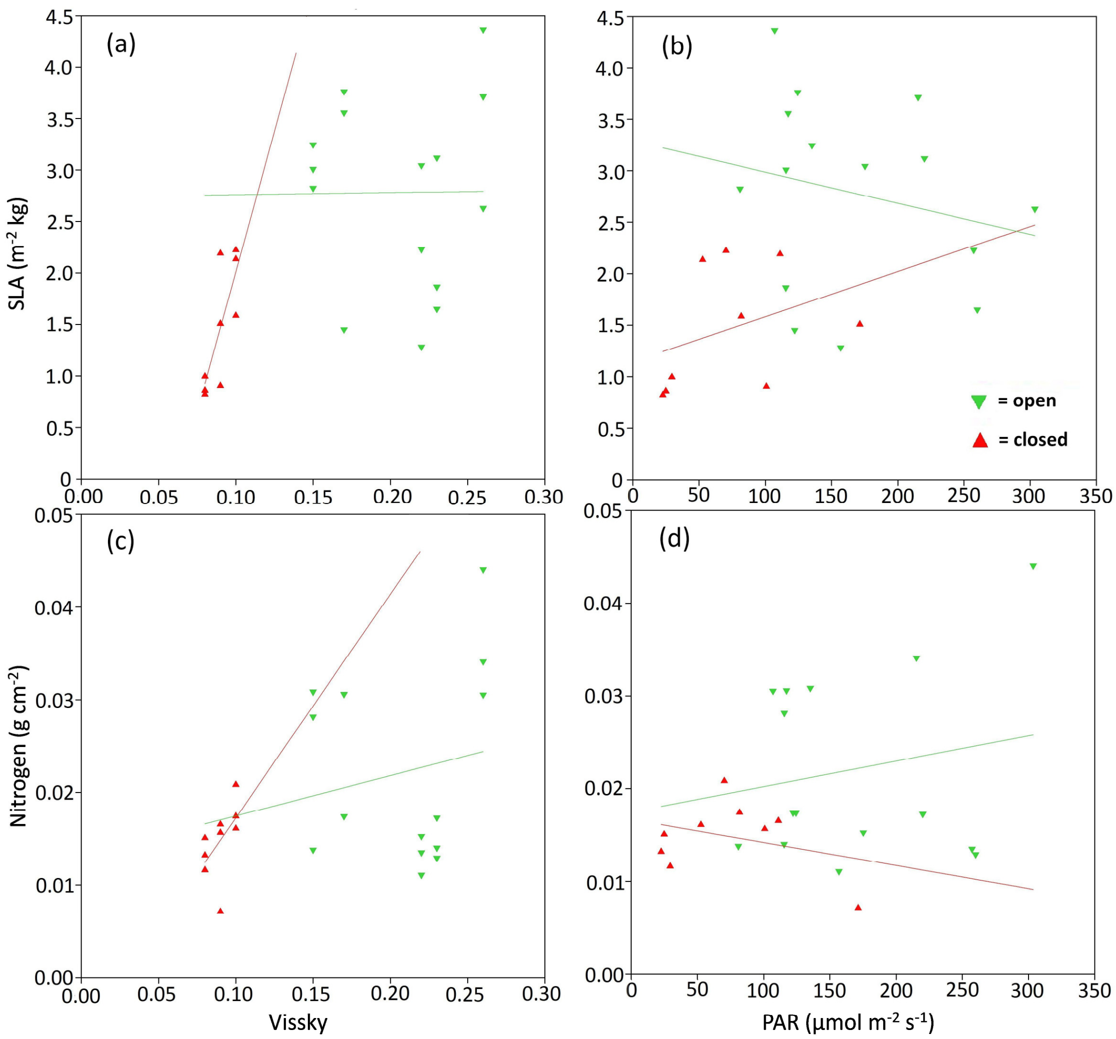

Figure 4.5 The relationship of (a) Vissky with SLA, (b) Vissky with nitrogen, (c) PAR with SLA and (d) PAR with nitrogen. For both the open and closed plots with fitted linear regressions.

Accumulated analysis of variance, which shows whether data should be described by a single line, two different line with the same slopes or two separate lines with differing slopes, was carried out on the data sets. The results, shown in Figure 4.5, found that Vissky had a significant effect on Nitrogen ($p = 0.041$) and SLA ($p = 0.002$) though the effect of plot status (open or closed) was not significant.

An unbalanced ANOVA using day and plot status (open or closed) found statistically significant differences in dark adapted yield between day and plot status (open or closed) in 2009 (Figure 4.6). In 2010 there was a significant difference between sample days but not between open and closed plots. There was only a small range in dark adapted yield: 0.79 to 0.84 in 2009 and 0.73 to 0.8 in 2010 (Figure 4.6).

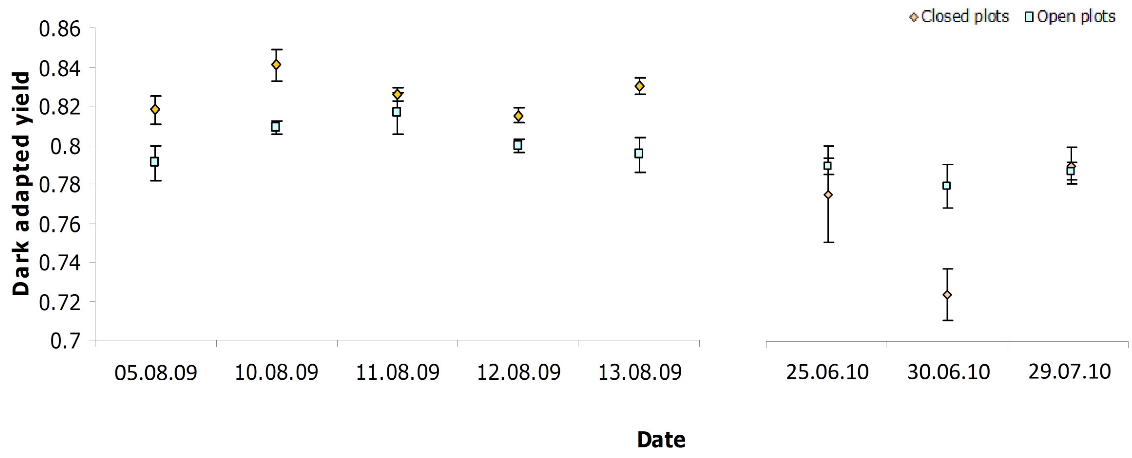

Figure 4.6 The dark adapted yield of Photosystem two (PSII) ± one SE during 2009 and 2010.

Outputs from the Chlorophyll fluorescence analysis during 2009 are shown in Figure 4.7a. Plot lines were fitted using a simple linear regression with groups, the groups being plot status (open/closed). The accumulated ANOVA shows that the data should be described by two separate lines with differing slopes. The majority of points associated with closed plots are at low levels of PAR, with all except one point below 250 µmol m^{-2} s^{-1}.

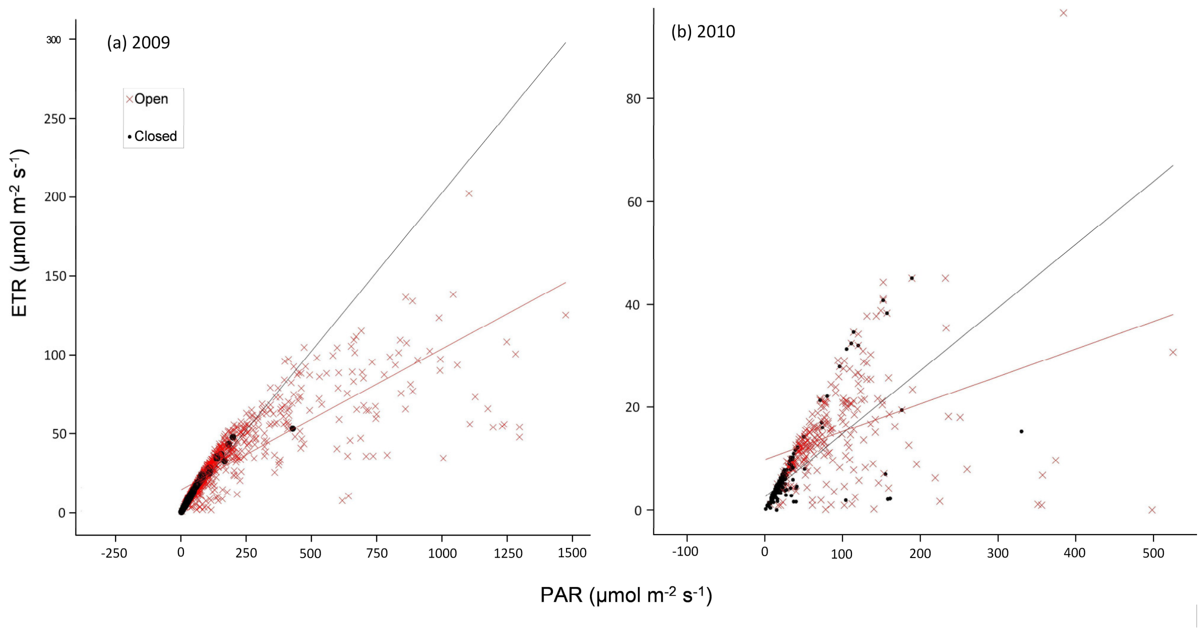

Figure 4.7 ETR plotted against PAR for the open and closed sampling plots during the (a) 2009 assessments and (b) 2010 assessments. The graph shows all instantaneous measurements of every seedling over the sampling days (n = 1625 in 2009 and n = 459 in 2010).

The PAR values recorded during the 2010 chlorophyll fluorescence assessment are lower than those from 2009, with almost all measurements below 500 µmol m^{-2} s^{-1}

(Figure 4.7b). Furthermore, the linear relationship between PAR and ETR shows much more spread, especially in the open plots. However, figures 4.6a and b show the majority of the values recorded in the closed plots fall below 250 µmol m^{-2} s^{-1}. In figure 4.7a the seedlings in the closed plots have very few values of ETR above 50 µmol m^{-2} s^{-1}, where as in open plots values reach up to 150 µmol m^{-2} s^{-1}. In 2010 the PAR measurements recorded are much lower and it is therefore not possible to evaluate whether higher values of ETR would be recorded in open plots at PAR values greater than 500 µmol m^{-2} s^{-1} (Figure 4.7b).

The relationship between *A* and PAR (Figure 4.8) shows more spread than the PAR and ETR relationships (Figures 4.7a and b). Regression analysis shows that whilst PAR has a significant effect on *A* ($p = 0.007$), the status of the canopy (open or closed) has no significant effect ($p = 0.326$). In addition the percentage accounted for on the fitted regression line was only 15.5%. In the closed plots there seems to be no relationship between PAR and photosynthesis. For similar measurements of PAR, *A* varies from -2 to over 4 µmol CO_2 m^{-2} s^{-1}.

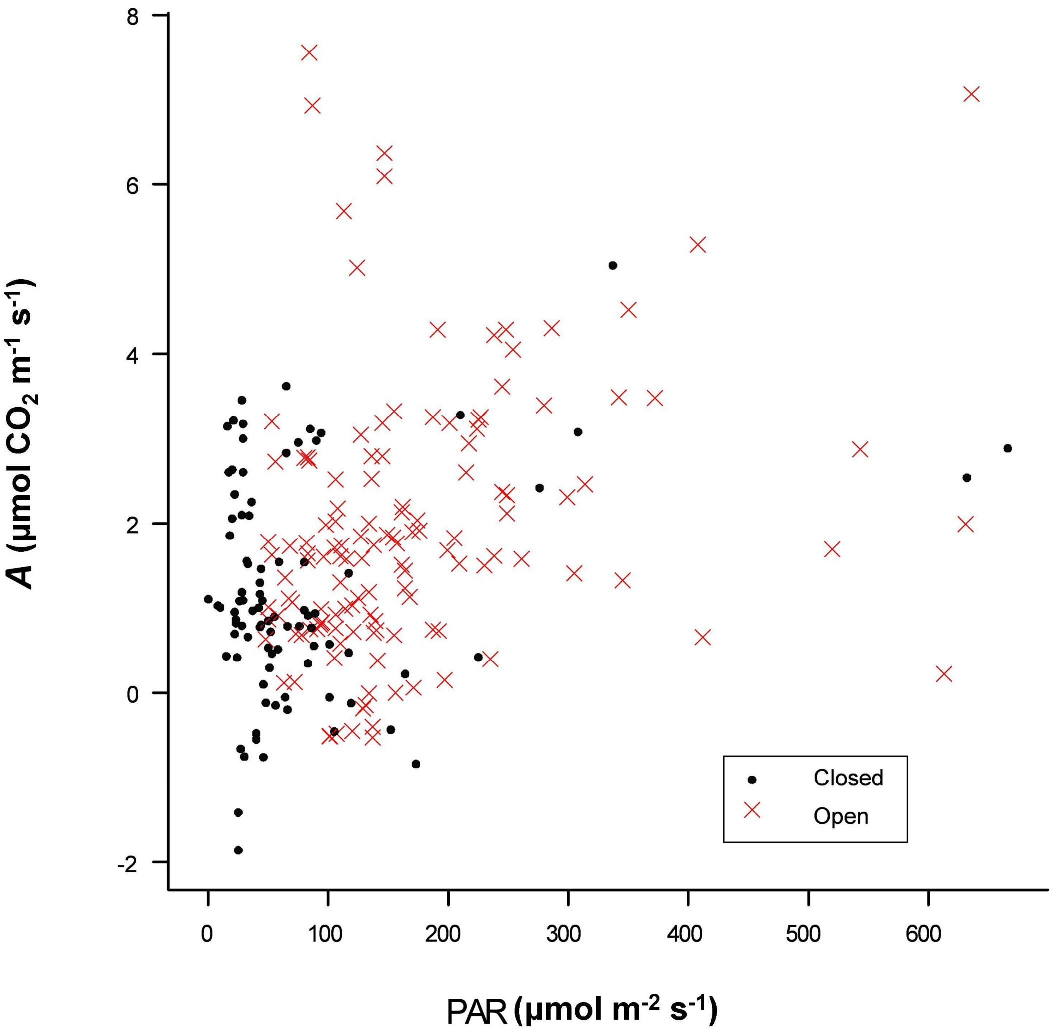

Figure 4.8 *A* (µmol CO_2 m^{-2} s^{-1}) plotted against PAR (µmol m^{-2} s^{-1}) grouped by plot status (open/closed). All measurements were all recorded during the 2010 assessment.

The relationship between *A* and ETR was also explored. The general trend showed an increase in photosynthetic rate for higher values of ETR ($p < 0.01$). However, the canopy status (open or closed) was not significant ($p = 0.748$) and the overall percentage variance accounted for was only 32.4 %.

4.4 Discussion

There are significant differences, in terms of morphology and physiology, between seedlings grown in open and closed plots. Although the majority of PAR values measured were below 100 µmol m^{-2} s^{-1} there were significant differences in PAR recorded in open and closed plots. As a result differences in the growth characteristics of the seedlings would be expected. Shade tolerant species such as firs and spruces have the ability to limit vertical growth and increase lateral growth in order to maximize light interception (Messier *et al.*, 1999; Claveau *et al.*, 2005). Sitka spruce is described as being either light demanding or of intermediate shade tolerance (Hart, 1991; Hale, 2004). However, it seems likely that Sitka spruce has a degree of plasticity as it has been shown, like Norway spruce and Silver fir, that it exhibits changes in morphology based on light availability (Page *et al.*, 2001; Grassi and Giannini, 2005). Page *et al.* (2001) find that the ADR, which is the ratio of the leader to the lateral growth of the first whorl, decreases with increasing basal area. An ADR of one or more would be expected in seedlings that are not light stressed (Page *et al.*, 2001; Grassi and Giannini, 2005) and to achieve 50 percent of the growth possible in full light a basal area of 30m^2 ha^{-1} is suggested for Sitka spruce (Page *et al.*, 2001; Hale, 2004). The results from this study are in accordance with those previously mentioned though plot C3 had a basal area of 41.2 m^2 ha^{-1} and an ADR of 1.07 whilst plot O5 had a basal area of 44.72 m^2 ha^{-1} and an ADR of 1.27. This emphasises that basal area is not always a good indicator of canopy openness. Furthermore, canopy-scope measurements show a poor link with canopy openness when sampling individual points (Hale and Brown, 2005) though the difference between open and closed canopy plots was significant in this study. Measuring visible sky or canopy closure using hemispherical photography provides a simple and more robust method of estimating below canopy light levels (Paletto and Tosi, 2009). In this study, the hemispherical photographs were taken after the seedling physiology measurements were recorded. Although it was known that basal area is not an ideal indicator of canopy openness (Hale, 2004) it was not expected that the differences in canopy openness would necessitate the recategorisation of one plot. Ideally the hemispherical photographs would have been taken prior to measurements taking place but unfortunately this was not possible due to a number of factors, the primary being uniform overcast sky, no rain and low wind are needed in order to take usable images (Hale, 2005b). Deans *et al.* (1992) report sturdiness quotients for six different clones from half sibling families of Sitka spruce. Their findings are similar to those measured in this study, ranging from 38.6 to 50. Fennessy *et al.* (2000) report slightly higher values, though in a similar range, for Radiata pine (*Pinus radiata* (D. Don)) ranging from 45 at higher elevations to 60 at lower elevations.

It is also expected that some of the physical measurements recorded would vary with both the PAR and Vissky measurements. However, the only obvious relationships found were between PAR/Vissky and Nitrogen content/SLA. SLA is positively correlated with potential relative growth, with larger values in general found in resource rich environments (Cornelissen *et al.*, 2003). It is therefore unsurprising that it is higher in the open plots where there is significantly more light available to the seedlings. The relationship between Nitrogen content and PAR/Vissky is also expected as nitrogen content has been shown to positively correlate with SLA and higher productivity sites (Poorter and De Jong, 1999).

PAR levels recorded in the plots are low and it is therefore unlikely that photoinhibition and damage to PSII would occur. However, when looking at chlorophyll fluorescence, the ETR at any given value of PAR is generally lower in open plots than in closed plots. Damage to PSII prior to measurement periods could theoretically be the cause of this as Sitka spruce seedlings subjected to high levels of light can show inhibited photosynthesis for up to six days due to high photorespiratory activity and damage to PSII (Black *et al.*, 2005). Nutrient status of the soil is another possible contributing factor as the seedlings are more susceptible to photoinhibition in nutrient poor areas (Grassi *et al.*, 2001). However, the dark adapted yield of all seedlings was around 0.8. A value of less than 0.8 would be expected in seedlings under environmental stress (Bertin *et al.*, 2009a). As this is not the case it indicates poor nutrient soil status or photoinhibition due to exposure to high PAR are not likely to be responsible for low values of ETR. The relationship between PAR and ETR is interesting as ETR values for closed plots are all below 50. As all these plots also have ADR values less than one, there is potential to develop ambient measures of ETR as an indicator of suitability for regeneration. Bertin *et al.* (2009b) investigated ETR in Sitka spruce in different light regimes. They found a linear relationship between light and ETR at low light levels but the relationship for both trees grown under low-light and high-light conditions levelled out around 500 μmol m^{-2} s^{-1}at different values of ETR. Therefore there is potential to use ETR measurements to indicate site suitability for seedling growth though differentiating between seedlings in different light regimes may necessitate ADR measurements. Unfortunately this study did not record many measurements of PAR in excess of 500 μmol m^{-2} s^{-1} and therefore it is not possible to ascertain whether the PAR/ETR relationship is similar in this case. The use of rapid light response curves (RLC), as used by Bertin *et al.* (2009b), is a potential way to solve this problem.

The relationship between *A* and PAR, although positive, is not strong. In open plots *A* increases with PAR but in closed plots there is no obvious relationship. Seedlings in the closed plots are more likely to have shade adapted leaves which tend to have fewer stomata, a thinner layer of chlorophyll-containing parenchyma, a lower specific leaf mass and a lower leaf photosynthetic compensation point and rate of saturation (Carter and Smith, 1985; Abrams and Kubiske, 1990). However this would only explain a different relationship, not the absence of one. The lack of a linear relationship between *A* and PAR may result from photosynthetic performance varying between leaves and seedlings (Genty and Meyer, 1995).

A linear relationship between *A* and ETR was not observed although has been reported under controlled conditions for both herbaceous species and woody perennials (Genty *et al.*, 1989; Harbinson *et al.*, 1990; Edwards and Baker, 1993; Tsuyama *et al.*, 2003). However the ambient measurements recorded during this study were from field assessments where climatic conditions are not controlled. As the measurements of chlorophyll fluorescence and gas exchange were not recorded simultaneously, inherent fluctuating climatic conditions may result in a poor relationship. In C4 plants there is a linear link between PSII activity and carbon fixation (Edwards and Baker, 1993). However, in C3 plants such as Sitka spruce, PSII activity is partitioned between photorespiration and photosynthesis which complicates the relationship between carbon fixation and PSII activity (Krall and Edwards, 1992).

4.5 Conclusions

Studies of seedling physiology have the potential to yield essential information to inform the management of regeneration in CCF. These results show that choosing the correct method to assess incident light in the understory is essential as the correlation between basal area and canopy openness does not always hold true. There is a clear difference in the growth characteristics of Sitka spruce seedlings grown under different canopy conditions that support previous findings regarding ADR values for Sitka spruce. Simple physical measurements such as this could prove valuable when making decisions on management interventions. In addition, the values of ETR in closed plots are almost entirely below 50 µmol m^{-2} s^{-1}, with PAR values less than 250 µmol m^{-2} s^{-1}. Further measurements over a wider range of PAR values could prove useful for characterising the suitability of particular sites for successful regeneration. Alternatively, RLCs could be used in ensure a wide range of PAR values are covered.

Whilst there was a good correlation between ambient PAR and chlorophyll fluorescence, a relationship between gas-exchange and chlorophyll fluorescence was not observed. This may have resulted from measurements not taking place simultaneously or from a lack of controlled conditions. However, it does indicate that without further investigation, gas-exchange data can not be inferred from chlorophyll fluorometry measurements taken under ambient light conditions in the field.

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4.8 Supplementary information: The theory of Gas-exchange and Chlorophyll fluorescence analysis.

When light is absorbed by chlorophyll pigments in a leaf there are three possible fates it can undergo. It can be used for photosynthesis, dissipated as heat or reemitted as light. This reemitted light is termed chlorophyll fluorescence and can be used to inform us about photosynthesis and heat dissipation as all three processes are in competition with one another (Maxwell and Johnson, 2000). Although only one to two percent of the incoming light is reemitted as chlorophyll fluorescence it is relatively easy to detect as it is reemitted at a longer wavelength (Genty *et al.*, 1989). As a result a leaf can be exposed to light of a certain wavelength. The light that is reemitted at a longer wavelength is measured and fluorescence can be calculated. This study uses a pulse-amplitude-modulation (PAM) fluorometer which distinguishes between ambient light and fluorescence reaching the sensor by modulating the light. This is done through rapidly turning on and off the measuring beam. In turn the emitted fluorescence follows the same on/off pattern and can be separated from background light (Heinz Walz GmbH, 1999).

A schematic of the gas exchange analyser can be seen in Figure 8. A is calculated using a gas-exchange analyser, in this case a LiCOR 6400. Air is taken into the system from the surrounding atmosphere. It then passes through two tubes. The first tube is filled with soda lime and removes CO_2 and the second is filled with silica gel beads that control the moisture content of the air. At this point a steady CO_2 concentration can be set by introducing CO_2 from a gas canister. The air then passes into two chambers contained within a measurement head. The sample chamber can be opened and clamped onto leaves to be measured where as the reference chamber is always empty and is used to calibrate the system. Calibration occurs when both chambers are empty. Within each of the chambers there is an infra red gas analyser (IRGA) capable of measuring concentrations of CO_2 in the system; one in the control chamber and the other in the sample chamber. The two IRGAs are calibrated when the sample cell is empty. When a sample is being measured, the CO_2 concentration and moisture content is measured in both the sample and reference chamber and by comparing these values, transpiration and A can be calculated. A clear window allows light into the sample chamber and a sensor in the measurement head (LiCOR, 2008).

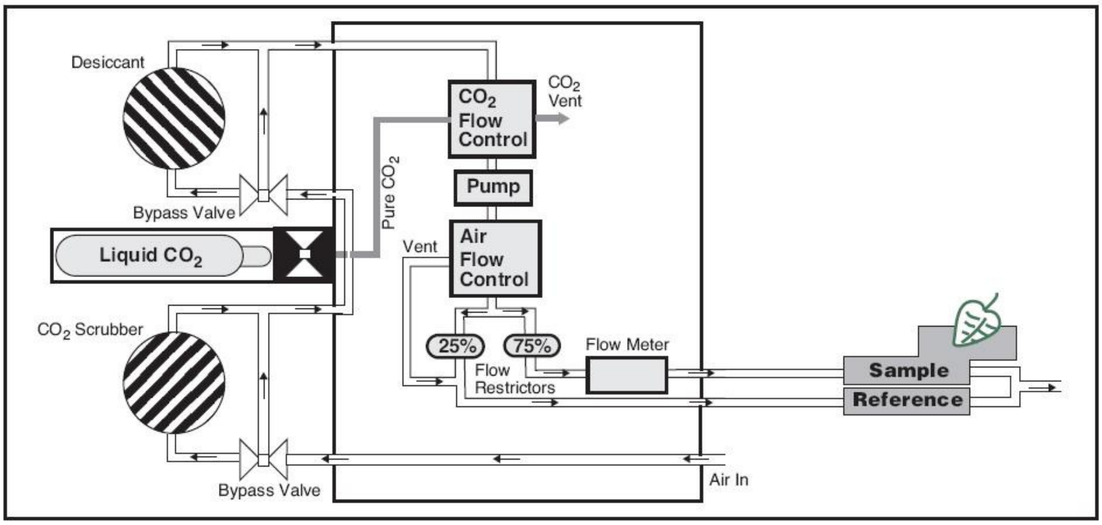

Figure 4.9 Schematic of the LICOR 6400 gas exchange analyser. Reproduced from LiCOR (2008).

Chapter 5

Modelling the effects of management on stand structure in an upland, irregular, coniferous forest

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Abstract

Since the early 1990s there has been increasing pressure on forest managers to meet multiple management objectives including recreation, biodiversity, aesthetics and timber production. As a result Continuous Cover Forestry has become increasingly popular as it is capable of delivering multiple management objectives. However, unlike Continental Europe, knowledge of how best to implement CCF is still developing in the UK. Simple models such as ideal reverse-J curves and Equilibrium Growing Stock can help inform current management but lack the ability to inform on the effects management decisions have on future stand structure, particularly over decadal time periods.

Spatially explicit process-based models provide an alternative to simple mathematical or conceptual models, because of their capacity to account for the multiple feedbacks associated with each management intervention. PICUS is a structurally detailed, 3D hybrid gap model capable of modelling uneven aged stands over decadal timescales. In this study the model was parameterised for Sitka spruce and run over two time periods (1954-2008 and 1954-2075) using data from local weather stations and an intermediate UK climate emissions scenario (UKCP09). The area modelled was a section of the Glentress Trial Area which has been undergoing transformation from clearfell - restock to CCF management since 1954, using a group selection system. The effects of management on stand structure were investigated using management scenarios including non-intervention, thinning to a residual basal area, and group selection system both with and without underplanting the canopy.

The model output indicates that thinning to a residual basal area is the best option to achieve an irregular structure, producing a reverse-J shaped diameter distribution and values of the tree frequency diminution coefficient q similar to those found in continental Europe. The q values drop between 2008 and 2075 for the residual basal thinning scenarios which conforms to observed records from both the Glentress Trial Area and a similar trial at Faskally (near Dunkeld). Outputs including tree density and basal area from the group selection scenarios can be improved relative to the

actual stand structure through underplanting early in the cycle. It is likely that this occurred at Glentress but a lack of comprehensive records on management interventions makes it difficult to establish why the simulated data differs from reality in many of the adopted modelling scenarios.

In situ carbon storage was also analysed for all management scenarios, with the non-intervention resulting in the highest carbon storage in both 2008 (830.82 tCO_2 ha^{-1}) and 2075 (1352.85 tCO_2 ha^{-1}). All management scenarios showed an increase in *in situ* storage between 2008 and 2075 model runs. However, the group selection systems, where a proportion of the canopy was retained, showed a larger increase in carbon storage than thinning to a residual basal area. The Woodland Carbon Code (WCC) look-up tables were used to compare the output from PICUS for the non-intervention and one residual basal area thinning. The WCC look-up tables produced slightly lower estimates though this is not unexpected due to differences in model initialisation and thinning prescriptions.

5.1 Introduction

Continuous Cover Forestry (CCF) is an approach to forest management that generally favours two or more canopy layers, avoids clearfelling (areas greater than 0.25 hectares) and promotes natural regeneration and a mixture of species (Mason *et al.*, 1999). The approach is currently being encouraged by policy which promotes a strategy to diversify forests, which in the past have been dominated by single species even-aged stands (UK Forestry Standard (Forestry Commission, 2011b); UK Woodland Assurance Scheme (Forestry Commission, 2011c). However, there are limitations to the implementation of CCF in Britain, the two major constraints being windthrow and unfavourable conditions for natural regeneration (Mason *et al.*, 1999). In addition, there is a further significant limitation: a lack of knowledge and experience of CCF amongst forest managers. CCF management in areas of continental Europe, such as Slovenia, has been widely used for long periods of time and forest managers have a good knowledge of how to implement a wide range of silvicultural systems (Helliwell, 1997; Pommerening and Murphy, 2004).

In these relatively early stages of CCF management in the UK, forest managers require clear guidance on how to transform even-aged stands to continuous cover (Mason and Kerr, 2004) and, once formed, how to manage CCF stands (Kerr, 2002). A number of studies in the recent past have helped develop a knowledge base for this in Britain, with many using established simple models such as the reverse-J (Hart, 1995; Mason *et al.*, 1999; Wilson *et al.*, 1999; Malcolm *et al.*, 2001; Kerr, 2002; Hale and Kerr, 2009; Poore and Kerr, 2009b; Cameron and Hands, 2010) and the Equilibrium Growing Stock (EGS) (Paterson, 1958; Poore, 2007; Poore and Kerr, 2009b). These simple models can be easily implemented and involve the use of only a few, relatively easily measured stand parameters. Both of these simple models involve the creation of an ideal structure based on current management goals and its comparison to the current stand structure. Management interventions are then implemented to attempt to move stand structure closer to the idealised scenario. However, they lack the capability to make predictions of future stand structure and are thus limited in use for investigating the effects that current management strategies can have on stand structure. PICUS v1.41 is a hybrid patch model that combines a classical successional gap model (Lexer and Honninger, 2001) with a process based production model; 3PG (Landsberg and Waring, 1997). It is capable of simulating changes in stand structure due to the effects of both management and changes in climate and is capable of modelling stands with an irregular structure. In addition it has been shown to produce realistic outputs in terms of stand structure and species composition for uneven-aged conifer forests in the eastern Alps of Austria (Lexer and Honninger, 2001; Seidl *et al.*, 2005) and has been successfully used when investigating the effects of management on the carbon storage capabilities of stands (Seidl *et al.*, 2007; Seidl *et al.*, 2008).

The Glentress Trial Area is one of the longest running trails of the transformation to CCF in the world, and the oldest in the UK (Kerr *et al.*, 2010a). It therefore offers a unique opportunity to test the model parameterisation and investigate the effects of implementing different management scenarios on the temporal development of stand structure. Sitka spruce was the species chosen for parameterisation as it is the most abundant species in Scotland, constituting 41% of total woodland cover (Forestry Commission, 2011a) and is the most abundant species (43%) in the Glentress Trial Area (Mackintosh *et al.*, 2011). As the model also outputs whole-tree carbon per hectare it will also be able to compare how *in situ* carbon storage varies between scenarios. The WCC look-up tables provide another method of estimating carbon sequestration.

The tables use a spreadsheet based approach is a quick and easy way of estimating carbon sequestration in even-aged stands based on thinning regime, initial plant spacing and the yield class of the site. As a result, for the even aged scenarios explored (scenarios one and two) it will also be possible to establish how output from PICUS v1.4 compares to Woodland Carbon Code (WCC) look-up tables (West and Matthews, 2011).

The objectives of this study were to:

1. Parameterize PICUS v1.41 for Sitka spruce in a Scottish upland forest.

2. To examine the effect of management on stand structure. The output from the management scenarios were compared to an assessment of stand structure that took

place in 2008 and in temporal forecasting were compared with each other to assess the impacts management has on future stand structure.

3. To identify possible improvements to the model parameterisation based on the findings of objective two.

4. To assess differences in whole tree carbon estimates from PICUS v1.4 and the WCC look-up tables.

5.2 Methods

5.2.1 Site description

Glentress forest is situated 25 miles south of Edinburgh, approximately two miles east of Peebles (Longitude 3° 9' W, Latitude 55° 40'N). Its total area is 1140 ha with the Trial Area making up approximately 117 ha. The area that was chosen for modelling is a 6.8 ha subsection of Block C (Figure 5.1). It is situated to in the north-east section of the Trial Area. The percentage number of trees (>7 cm DBH) in the area that are Sitka spruce is 93.3%. The soil type, which is derived from Ordovician sediments, is a peaty surface-water gley, often with an iron pan. The altitude of the area is approximately 530 m. The general aspect of the Trial Area is southerly and the annual precipitation is between 1000 and 1500 mm (Malcolm, 1992).

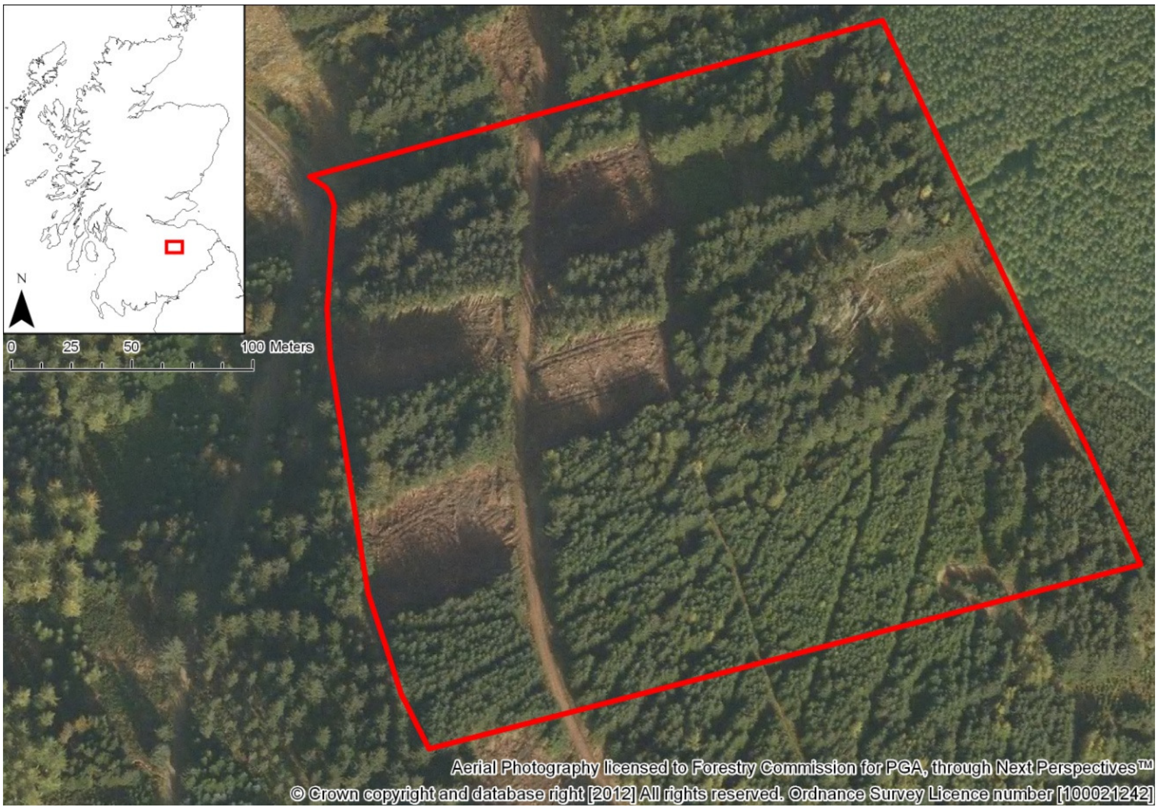

Figure 5.1 Aerial photograph of the modelled area, C2.

5.2.2 Simulation Model: PICUS v1.4

PICUS V1.41 is a hybrid gap model capable of simulating heterogeneous stand structures. It is a hybrid of the three dimensional gap-model PICUS v1.2 and the physiological model Physiological Principles in Predicting Growth (3-PG) model (Seidl *et al.*, 2005). It is based on a 3D core structure that is made up of discrete patches; 10 m by 10 m, with a depth of 5 m. However, unlike many gap models this unit is not viewed as a point, it is viewed as an interactive unit which can interact with surrounding units. This study modelled an area of 1.2 ha (100 m x 120 m) as 30 discrete patches. PICUS incorporates a light attenuation model which accounts for both direct and diffuse light. Tree growth is based on growth potential derived from open grown trees that is then modified due to environmental constraints (Lexer and Honninger, 2001). Stand level productivity is estimated by the 3-PG component. Gross Primary Production (GPP) is calculated by multiplying the photosynthetically active radiation intercepted by the canopy by the quantum efficiency of the canopy, this latest quantity being calculated based on environmental effects. Net Primary Production (NPP) is then calculated as a constant fraction of GPP (A ratio of 0.45 was used (Landsberg and Waring, 1997). Having established NPP, biomass is then allocated to trees based on their relative success within the patch model environment (Seidl *et al.* 2005). Regeneration and mortality are predicted using the gap model approach. New trees are generated stochastically by a recruitment submodel, with new tree growth being modelled once it reaches a diameter at breast height (DBH) of one centimetre (Seidl *et al.*, 2005). PICUS uses available light in the lowest canopy layer, seed production, seed dispersal and site characteristics in order to establish when and where regeneration occurs (Lexer and Honninger, 2001). The probability of tree mortality is calculated based on an intrinsic risk of death which is not affected by tree growth or size, but augmented by a stress factor based on the failure to achieve a threshold diameter increment over a specified number of years (Lexer and Honninger, 2001). Management within the model is flexible, allowing virtually any kind of management down to the single tree scale. Management operations are written as scripts that can be called in specific years to be carried out. Planting operations are flexible with the user defining the size, density and spatial location of seedlings and saplings via input tables (Seidl *et al.*, 2007).

5.2.3 Climate data

The climate data required to run the model are mean monthly values of precipitation (mm), temperature (^{o}C), incoming net solar radiation (MJ m^{-2}) and vapour pressure deficit (VPD) (kPa) (Figure 5.2). For the period from 1954 to 2011 the majority of the weather data was extracted from the British Atmospheric Data Centre (BADC) online records. As the Glentress weather station only had temperature and precipitation data, additional data was gathered from the nearby weather stations. Data from the Glentress weather station was given preference where possible. If data were unavailable for a specific time period it was then sought from Eskdale Muir (27 miles distant) or failing that, Hallmanor House (43 miles distant). PICUS v1.4 requires the four variables as monthly averages, therefore where weather station data were given in a different time format they were converted to mean, monthly values for use in the model. For the few exceptions where there were still gaps in the data set, modelled weather data from the UKCP09 were used (Figure 5.2).

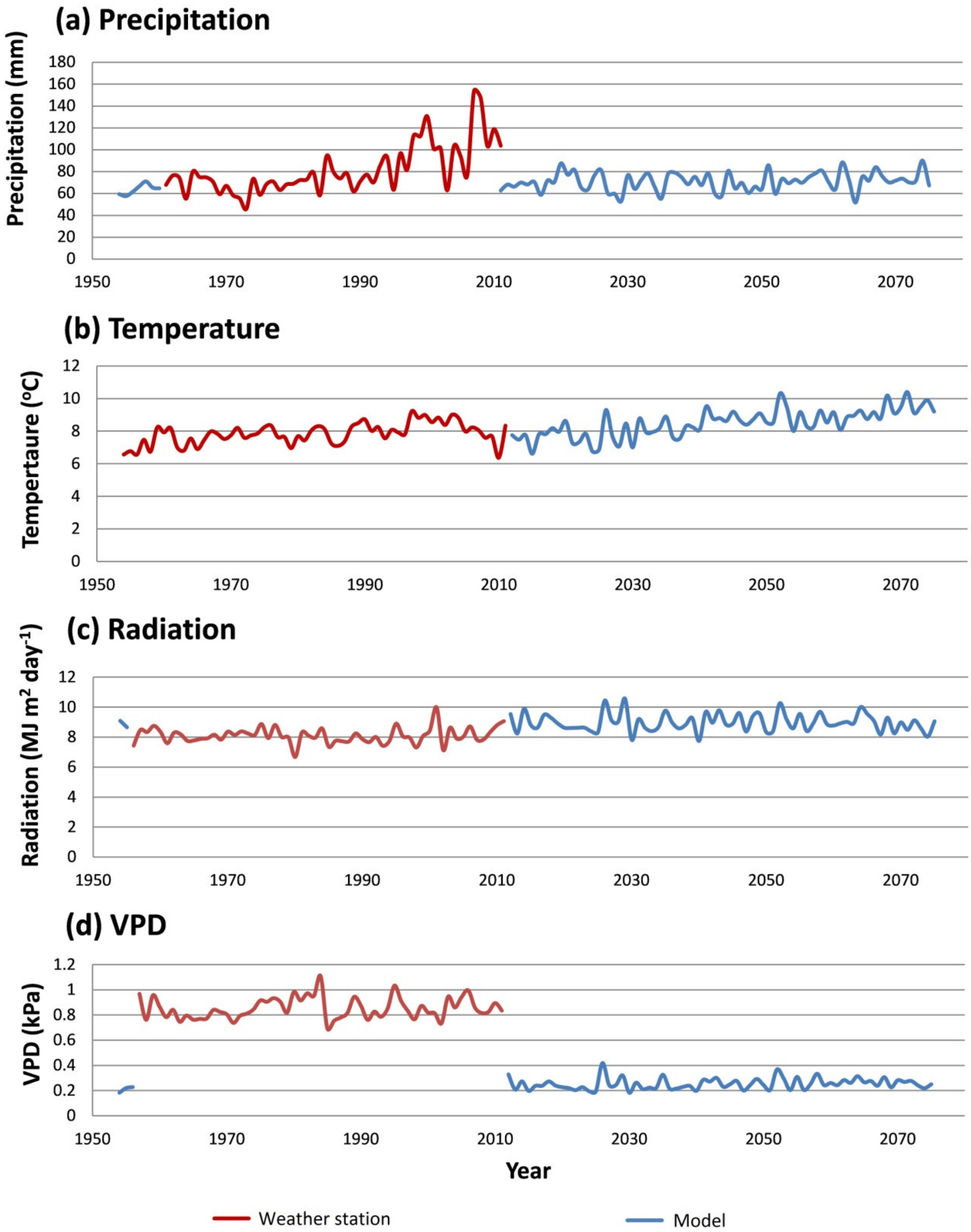

Figure 5.2 The (a) precipitation, (b) temperature, (c) radiation and (d) VPD climate values used for the management scenarios. The data plotted are annual averages, with the modelled data in blue and actual measurements in red.

The predicted climate data used for the scenarios from 2011 until 2075 were acquired from UKCP09 (Environment Agency, 2009). A spatially coherent version of the medium scenario was used that is based on the Hadley Regional Model, HADRM3-PPE. The model produces output for 25 km^2 areas over a national grid (Environment

Agency, 2012). The data for this study were extracted from grid ID: 845. VPD was calculated from the relative humidity predictions produced by the model. There is a clear difference between the modelled and measured VPD values. This was not initially obvious as in creating Figure 5.2d, monthly values were converted to yearly averages. However, of the four climatic drivers, precipitation and temperature are the two that have been shown to affect productivity (Seidl *et al.*, 2005)

5.2.4 Parameter list

Parameters were acquired from a combination of literature review, personal communications and unpublished data sets (Table 5.1). Where parameters for Sitka spruce were unavailable, the values used for the parameterisation of Norway spruce in Austria were used (see appendix 1 for full parameter requirements of PICUS v1.4).

Table 5.1 The parameter list, along with their sources, used to parameterise PICIS V1.4 for Sitka spruce.

Parameter	Value	Source
Growth, biometrics and allometry		
Wood density	388 kg m^{-3}	Pers. Comm. Barry Gardner
Biomass expansion factor	1.438	Levy *et al.* (2004)
Maximum height	58 metres	Mitchell (1974)
Maximum DBH (at 1.5m)	239 cm	Mitchell (1974)
Foliage Biomass (oven dry)	5.3775 kg BM*	Highland Birchwoods biomass database
Stem biomass allometry	a = 0.2207 b = 2.3701	Local volume sample trees
Specific leaf area	6.1 m^2 kg^{-1} **	Highland Birchwoods biomass database
Diameter height parameters	a = 0.1863	Glentress sample trees
Environmental responses		
Growing Degree Days		
Minimum	650 day degrees over 5°C	Pers. Comm. Duncan ray
Optimal	1400 day degrees over 5 °C	
pH response		Pers. Comm. Duncan Ray
Minimum	pH 4.0	
Optimum	pH 6.0	
Light tolerance class	light demanding – intermediate	Hale (2004)
Seed production and regeneration		
Maximum age	750 years	Urban *et al.* (1993)
Seed year interval	4 years	Gosling (2007)
Age at first seed production	30 years	Gosling (2007)
Maximum seed number per tree	3 000 000	Gosling (2007)
Maximum germination percentage	10 %	Gosling (2007)
Carbon and nitrogen cycling		
C/N ratio foliage	83.1	Black *et al.* (2009)
C/N ratio fine roots	76.6	Black *et al.* (2009)
C/N ratio coarse roots	221.0	Black *et al.* (2009)
C/N ratio wood	224.7	Black *et al.* (2009)

* data is based on measurements taken from nine Sitka spruce trees sampled from Glenmalure forest, Ireland.

** data is based on measurements taken from 12 Sitka spruce trees sampled from Cloich forest.

5.2.5 Experimental design

Management scenarios

Six scenarios were chosen in order to investigate the consequences different approaches to management may have caused since 1954, the year when conversion to CCF began in area C2. These ranged from a non-interventionist approach (scenario one) through to a relatively complex group selection system with underplanting (scenarios five and six). Initialisation of the scenarios was based on plot based mensuration data from 1954 archives (Table 5.2). Unfortunately they were not spatially explicit and therefore the values for the whole of Block C (~20 ha) were used as opposed to area C2.

Table 5.2 The composition of Block C in 1954 where all trees were Sitka spruce. These data were used for the initialisation of the model.

Diameter class (cm)	Number of trees per ha
13-17	169
18-22	73
23-27	30
28-32	14
33-37	6
38-42	2
43-47	1

The six scenarios were as follows:

Scenario 1: Stand initialised based on the records for Block C from 1954 (Table 5.2). No management interventions were implemented after 1954.

Scenario 2: Stand initialised based on the records for Block C from 1954 (Table 5.2). Thinning to a residual basal area of 35 m^2 ha^{-1} on a six-year cycle. This threshold basal area was chosen based on top height and tariff data collected in the Trial Area and conforms to the thinning control procedures outlined in Rollinson (1985). Only trees over 7cm DBH were considered for thinning and selection was random.

Scenario 3: Stand initialised based on the records for Block C from 1954 (Table 5.2). Thinning to a residual basal area of 25 m^2 ha^{-1} on a six-year cycle as per the Glentress management plan proposed by Kerr *et al.*(2010b). Only trees over 7cm DBH were considered for thinning and selection was random.

Scenario 4: Stand initialised based on the records for Block C from 1954 (Table 5.2). Every six years between two and three groups were felled (each group 20 by 20 metres) and the remaining crop was not thinned. Over a sixty year period 20% of the stand was left as long term retention.

Scenario 5: Stand initialised based on the records for Block C from 1954 (Table 5.2). Every six years between two and three groups were felled (each group 20 by 20 metres). Over a sixty year period 20% of the stand was left as long term retention. An underplanting of 3000 Sitka spruce seedlings occurred in 1966.

Scenario 6: A modified version of scenario 5, in which a second underplanting took place in 2026.

The felling patterns adopted for Scenarios 4, 5 and 6 were employed to mimic the group selection system that was used in the Glentress trial area from 1952 to 2010 (Kerr *et al.* 2010a; Kerr *et al.* 2010b).

All the scenarios were run over two different time periods. The first time period was 1954 to 2008. These dates were chosen as 1954 was the year when the area begun its transformation to CCF and 2008 is when the last assessment of all the permanent sample plots across the trial area took place. The results of the 2008 assessment are reported in chapter to of this thesis allowing comparison between actual stand structure and model output.

The second time period was 1954 to 2075. This allowed a comparison of the effects that different management scenarios may have had on future stand structure. The second time period allowed two complete cycles of management to be completed, each cycle being 60 years.

There are very few stochastic elements to the model (transfer from snags to detrital pools, tree mortality, seed year frequency and seedling establishment), but their effects on model output was considered by running scenario two 10 times for the period between 1954 and 2008 and calculating the resulting variability in the stand variables (*i.e*. basal area, stems per hectare and standing volume). Having established that the effects of stochastic processes on these state variables was minimal, all the other scenarios for both time periods were run three times.

5.2.6 Comparison of scenarios

Comparisons of the output from the different scenarios were made based on classic stand development indices: basal area (m^2 ha^{-1}), stems per hectare (n ha^{-1}) and standing volume (m^3 ha^{-1}). In addition, the diameter distributions for each scenario were examined over both time periods. Negative exponential regressions were fitted to the diameter distributions and their key characteristics explored. These included the percentage variance explained by the fitted negative exponential, the coefficients q and k. The diminution coefficient (q) is the average ratio of trees in one diameter class divided by the number of trees in the next larger diameter class and k is the intersection of the regression when x = 0 and, in the context of CCF, describes the necessary recruitment of saplings developing into trees for the structure to be sustainable (Meyer, 1952). The fitting of the negative exponentials and the calculation of the fitted parameters were done in Genstat 11th edition (VSN International Ltd. Hemel Hempstead, UK) and utilised the same methodology outlined in Mackintosh *et al.* (2011).

5.2.7 Carbon estimates

One of the outputs from PICUS v1.4 is whole-tree carbon per hectare. This was converted to CO_2 content by multiplying 44/12, *i.e.* the ratio of the two molecular weights. The values for scenarios 1 and 2 were compared with values calculated from the WCC look-up tables (West and Matthews, 2011). The WCC look-up tables allow the cumulative carbon sequestration per hectare to be calculated. The calculation, as with PICUS v1.4, uses the whole tree in these calculations. It is driven by just a few simple parameters: tree species, the spacing used when planting, the yield class and type of management. At present management only covers a no thin and a standard thin (on a 5 yearly cycle) scenario. The output is in the form of cumulative total sequestration in 5 yearly periods. For this study, local timber yield for an equivalently located even-aged stand of Sitka spruce was estimated as 10.45 m^3 ha^{-1} $year^{-1}$ using the spatially explicit version of the Ecological Site Classification (Ray, 2001). This was then used in conjunction with a seedling spacing of 1.7m and both management options; “thin” or “no thin”. The WCC does not provide simulation of CCF management and therefore comparisons with scenarios three to six were not made.

5.3 Results

5.3.1 Summary of 2008 plot assessments

A brief summary of the results obtained from the 2008 sample plot assessments are shown in Table 5.3 and Figure 5.3. The results shown come from the assessment of 15 plots throughout the 6.8 ha area (see page 23).

Table 5.3 Stand characteristics of area C2 of the Glentress Trail Area measured during the 2008 permanent plots assessment.

Area	**Stems (ha^{-1})**	**Basal area (m^2 ha^{-1})**	**Standing volume (m^3 ha^{-1})**	**q**	**k**	**% variance**
C2	1235	36.62	163.27	1.89	1855	99.4

Figure 5.3 shows the actual diameter distribution sampled from area C2 of the Trial Area in 2008. It can be seen that there is a good fit between the data and the negative exponential regression (99.4 % variance accounted for (Table 5.3)). In contrast to the model runs, the number of trees recorded in the mid diameter classes fits well with the fitted negative exponential regression.

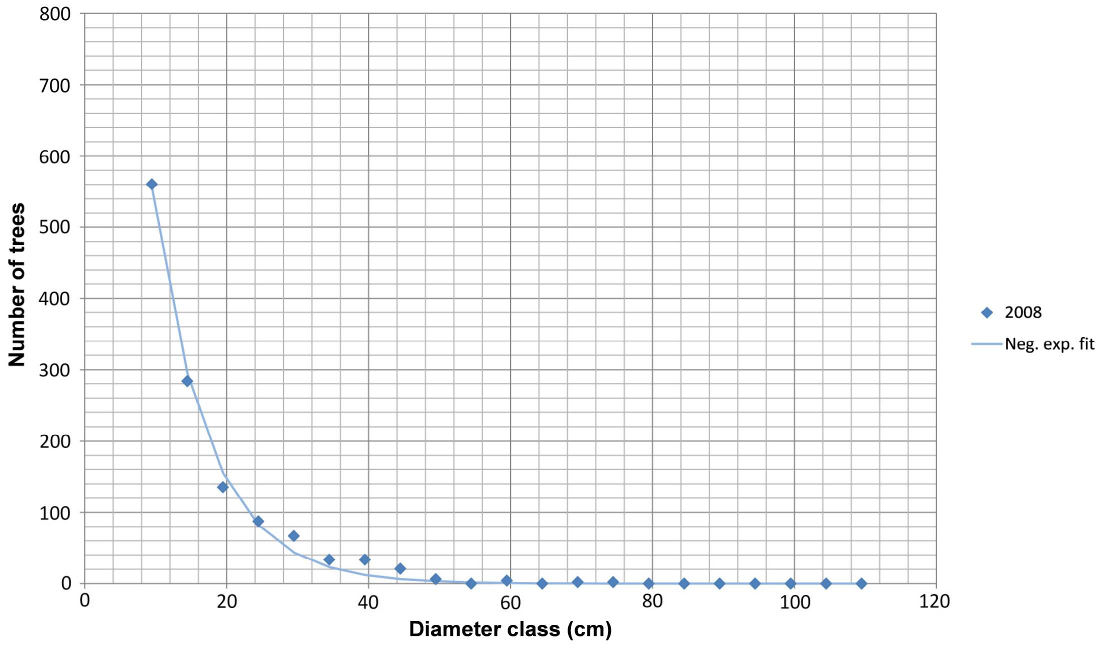

Figure 5.3 The number of trees by diameter class from the survey of permanent sample plots in 2008, fitted with a negative exponential regression (99.4 % variance accounted for).

5.3.2 Comparison of stand parameters

The six scenarios varied in their similarity to the stand parameters measured during the field assessment in 2008 (Table 5.4). Figures shown in tables 5.4 and 5.5 are averages over three separate runs except for model scenario 2 (1954-2008) which is an average over 10 runs.

Table 5.4 Predicted stand characteristics for 2008 and 2075, respectively the two final years of the management scenarios for the two time periods. Scenario 2 also shows ± one standard deviation.

Model runs	Stems per hectare	Basal area (m^2 ha^{-1})	Standing volume (m^3 ha^{-1})
1954 - 2008			
1	857	37.58	329.45
2	640 ± 59.77	28.95 ± 0.07	253.02 ± 2.35
3	469	20.60	175.76
4	1182	21.35	157.40
5	1212	27.70	194.02
6	1212	27.7	194.02
1954 - 2075			
1	520	53.74	547.92
2	526	29.40	271.92
3	447	21.21	172.81
4	1038	24.02	209.04
5	1160	26.13	225.68
6	1198	31.93	245.56

Scenario 1, which simulated no management interventions, produced the highest basal area in both 2008 (37.58 m^2 ha^{-1}) and 2075 (53.74 m^2 ha^{-1}). Similarly high values were found for the standing volumes. Both of these increased further between 2008 and 2075. Conversely, the number of trees decreased with the decline mainly occurring in the smallest diameter class (7-12 cm DBH) (Figure 5.4).

Scenario 2 showed a fairly steady basal area over time, likely due to this scenario's thinning regime being based on a threshold basal area. There was a decrease in number of trees over time from 640 in 2008 to 526 in 2075 with the losses occurring predominately in the smallest diameter class (Figure 5.4). The standing volume increased between the two time periods.

Scenario 3 showed very little change in between 2008 and 2075 and for both assessments had the lowest values for all stand characteristics.

Scenario 4 showed a slight decrease of 144 trees per hectare between 2008 and 2075 but an increase in basal area and standing volume over the same time period.

Scenario 5 resulted in the highest tree density of any of the scenarios in 2008 at 1212 trees per hectare. The 2075 run resulted in a slight decrease in tree density and basal area but an increase in volume relative to the 2008 runs.

Scenario 6, which is the same as scenario five but with a second underplanting in 2026, resulted in a higher tree density, basal area and volume than the equivalent scenario 5 run over the same time period.

5.3.3 Comparison of diameter distributions

There is considerable variation in the parameters derived from the fitted regressions and the diameter distributions simulated for the management scenarios (Table 5.5).

Table 5.5 Percent of explained variance and predicted parameters from the negative exponential regressions fitted to the data of 2008 and 2075 for the six scenarios over the two time periods, respectively. Figures shown are averages over three separate runs except for model scenario 2 (1954-2008), which is an average over 10 runs and shows ± one standard deviation.

Model runs	q	k	% variance
1954 - 2008			
1	11.57	61286	94.7
2	5.49 ± 0.65	10328 ± 3470	93.1
3	2.07	857	82.2
4	3.63	9756	99.0
5	1.629	1302	61.4
1954 - 2075			
1	1.16	103	27.0
2	1.50	356	93.4
3	1.46	286	98.2
4	3.41	7060	99.5
5	3.18	6717	98.8
6	2.08	2366	95.0

Scenario 1 had very high values of q and k and a good fit in terms of percentage explained variance in 2008. However, by 2075 both the q and k values had reached very low values and the percentage variance had reduced from 94.7% to 27.0 %.

Scenario 2 showed high values of q and k in 2008 but these dropped to values typical of CCF by 2075 (Schaeffer *et al.*, 1930; Gul *et al.*, 2005). The percentage of explained variance was over 90% in both 2008 and 2075.

Scenario 3 resulted in values of q and k in 2008 close to those typical of CCF stands throughout Europe, *i.e.* at 2.07 and 857 respectively. By 2075, these values fell within the accepted values of q for CCF (Gul *et al.*, 2005). The percentage of explained variance was only 82.2% in 2008 but rose to 98.2% in 2075.

Scenario 4 showed relatively high values of q and k with rather small reductions between the two time periods, resulting in the highest values of q (3.41) and k (7060) for any scenario in 2075. The percentage variance was over 99 percent in both 2008 and 2075.

Scenario 5 resulted in values of q and k at the upper-limit of the accepted values for CCF (i.e., q=1.6, k=1302). However, the 2075 run showed an increase in q and k relative to the 2008 run to very high values of 3.2 and 6717 respectively and also an increase in the percentage variance explained.

Scenario 6 differs from Scenario 5 only over the 1954-2075 period. The second underplanting resulted in lower values of q (2.08) and k (2366) than scenario 5 over the same period though the percentage of explained variance was similar.

Comparison of the scenario outputs and the actual stand data from 2008 (Table 5.3) shows that scenario 5, which best represents the actual management practice between 1954 and 2008, provides the most realistic output. The number of trees is very similar and although there is a basal area is underestimated and volume is overestimated, the values of q and k are close to those measured in 2008 (Tables 5.4 and 5.5). The output from the second simulated period (ending in 2075) shows that scenario 5 diverges from the stand values measured in 2008. However, Scenario 6, which only differs from Scenario 5 by having an extra underplanting in 2026, maintains stand characteristics similar to those recorded in 2008.

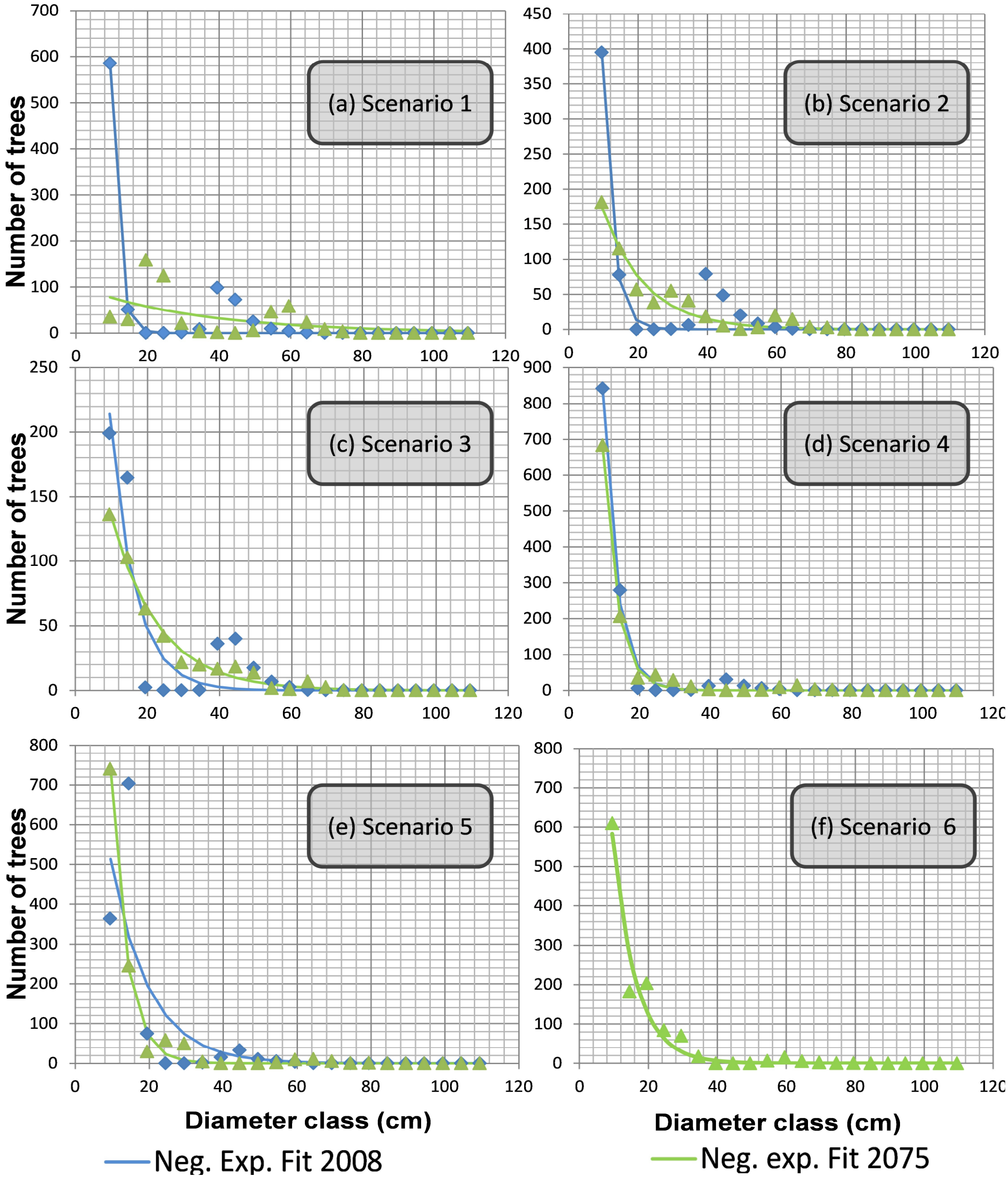

Figure 5.4 The diameter–frequency distributions with fitted negative exponential regressions for all six scenarios and for both time periods. Note the y-axis varies between scenarios.

In 2008 all scenarios show the same shape of diameter distribution, with many small trees in the small diameter classes and few in the large diameter classes (Figure 5.4). Following this, a second small peak is found in the intermediate diameter classes.

Despite these similar shapes, the number of trees in the smallest diameter class was variable, ranging from 214 trees for scenario 3 to 847 in scenario 4.

However, by 2075 the diameter distributions have started to differentiate among scenarios. Scenario 1 has two different frequency peaks; one at around 20 cm DBH and the other one at around 60 cm DBH. Scenarios 2 and 3 have more of a classic reverse-J shape, with a decrease in trees with increasing diameter class. The diameter distribution of scenario 4 remains relatively similar between 2008 and 2075, with only a small decrease in the number of trees in the smallest diameter class and very few larger trees. Scenario 5 is notable as it is the only scenario where the number of trees is lower in 2008 than 2075 in the smallest diameter class. Scenarios 5 and 6 differ only in that scenario 6 features a second underplanting. The effect of this underplanting is that fewer trees are found in the smallest diameter class and a less steep gradient results in a lower value of q (Table 5.5).

5.3.4 Stochastic elements

The average values and range of values over the 10 runs can be seen in Figure 5.5. There is very little variability in tree frequency across the entire diameter range except in the two smallest diameter classes where the range is 157 and 30 trees ha^{-1}, respectively. The diameter class with the largest range is the smallest, 7-12 cm, with a standard error of the mean of 18 trees ha^{-1}. Tables 5.4 and 5.5 show the mean values for Scenario two and the standard deviation for all stand characteristics. The standard deviation for volume and basal area is low, where as it is higher for stems per hectare and k.

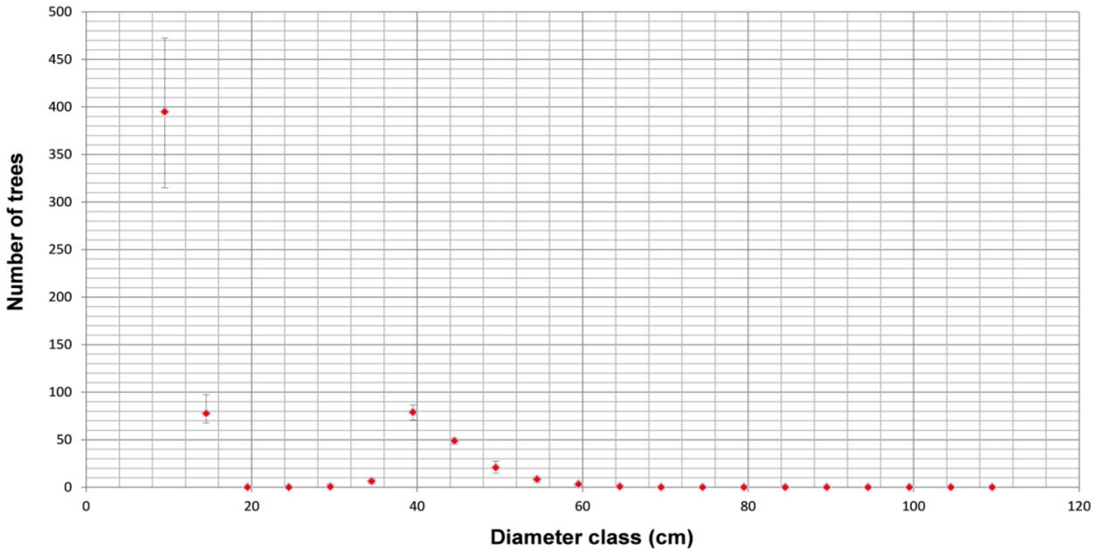

Figure 5.5 The average number of trees per hectare by diameter class for 10 runs of scenario 2 (1954-2008). The error bars show the range in number of trees over the ten runs.

5.3.5 Comparison of Carbon estimates

Where available (scenarios 1 and 2) comparisons with the WCC look-up tables showed that PICUS v1.4 resulted in higher estimates of *in situ* carbon storage (Table 5.6). Scenario 1 resulted in the highest levels of *in situ* carbon storage with values of 830.82 tCO_2 ha^{-1} in 2008 and 1352.85 tCO_2 ha^{-1} in 2075. As scenarios 2 and 3 involved thinning to a residual basal area, their *in situ* carbon storage remained relatively constant over the two time periods. Scenarios 4 to 6, all involving group selection but with differing degrees of underplanting, showed an increase in sequestered carbon by 2075. Scenario 6 had the highest *in situ* carbon storage of these three group selection scenarios by 2075 with a value of 623.19 tCO_2 ha^{-1}.

Table 5.6 *In situ* carbon as estimated by PICUS v1.4 and the WCC look-up tables for 2008 and 2075.

Management scenario	**Estímated CO_2 (tCO_2 ha^{-1})**			
	PICUS v1.4		**WCC look-up tables**	
	2008	**2075**	**2008**	**2075**
1	830.82	1352.85	641.5	863.8
2	649.62	668.46	393.1	500.2
3	460.06	465.02	-	-
4	420.62	510.49	-	-
5	506.59	580.96	-	-
6	506.59	623.19	-	-

5.4 Discussion

5.4.1 Comparison with actual stand assessment

The parameterisation of PICUS v1.41 for Sitka spruce in Southern Scotland has resulted in outputs that are realistic relative to the permanent sample plot data gathered in 2008.

Scenarios 5 and 6, both group selection systems with one and two underplantings respectively, mimicked the actual management practices most closely and therefore it is not surprising that their predicted stand characteristics were more similar than model outputs from scenarios 1 to 4 for 2008. The values of q, for both the simulation and stand assessment of area C2, are still higher than the 1.3-1.6 range typically found in continental Europe (Schaeffer *et al.*, 1930; Gul *et al.*, 2005) and in the Trial area as a whole (q=1.3) (Mackintosh *et al.*, 2011). However, this range of q values is based on values from continental selection systems. It is entirely possible to have a stand structure that adheres to the definitions of CCF as set out by the UK Forestry Standard (Forestry Commission, 2011b) and have values of q out with this range.

The underplanting had a large effect on stand structure. For example, after two management cycles, in 2075, the values of q and k from scenario 5 moved away from values typically found in CCF systems with q increasing to 3.18 indicating a rapid decrease in trees from one diameter class to the next. However, underplanting at an early stage in the second rotation (2026, Scenario 6) resulted in a reduction in q and k to values more akin to typical CCF stands.

On the negative side, the output from the model scenarios did not strictly resemble the actual stand structure in 2008 though it moved towards that structure by 2075. Only scenario 3 and scenario 5 have q and k values approaching the measured values from 2008. The following reasons may contribute to the discrepancy between reality and the model output:

- Since the start of CCF management in the Trial Area, the management interventions were specified by University of Edinburgh but were carried out by the Forestry Commission (Wilson *et al.*, 1999). As a result, there are scant detailed records of the exact interventions carried out over extended periods.
- There have been problems with grazing, initially with sheep and later with deer, which impacted on recruitment and growth of natural regeneration. These effects were not modelled in PICUS (Blyth and Malcolm, 1988).
- There have been problems with natural regeneration and an inconsistent methodology applied to restocking (Wilson *et al.*, 1999). When regeneration failed to develop after groups were felled, the area was often left to be colonised but in some cases re-planted.
- The initial stocking of area C2 was very low at only 295 trees per hectare, though this was likely supplemented with planting. The initial management plan suggested planting at no more than 3 by 3 feet (Anderson, 1955), but records are not detailed enough to establish whether and when this planting density was implemented, where lower densities were used and where natural regeneration was utilised. However, planting took place in the 1960s and it is likely that density increased to at least the standard 2500 seedlings per hectare (Hart, 1991).

Our experience is similar to the one described by Didion *et al.* (2009) and Seidl *et al.* (2005), both of whom highlight the difficulty of establishing the causes of the differences between simulated and actual output when the records of both natural and anthropogenic impacts on forests are not well documented.

5.4.2 Implications for management

The output from the model can yield valuable information regarding the effect management decisions can have on stand structure.

The output from Scenario 1 showed that non-intervention will result in a two tier structure. In 2008 this structure had many small trees (7-12cm DBH) and a sparse overtstorey (~40cm DBH) with a very high value of q (11.57). However, by 2075 the basal area had reached 53.74 $m^2\ ha^{-1}$ with the majority of trees located in the overstorey. CCF is sometimes called "close to nature" forestry (Mason *et al.*, 1999;

Pommerening and Murphy, 2004), but here non-intervention resulted in a long-term decrease in structural diversity.

Scenarios 2 and 3 are very similar as management was based on thinning to a residual basal area. Both scenarios resulted in reverse-J shaped diameter distributions in both 2008 and 2075. However, standing volume is low for both scenarios over both time periods relative to values typically found in continental Europe. Typical values for a fir-spruce forest in continental Europe range from 350 to 500 $m^3 ha^{-1}$ (Schutz, 2002b; Medarevic *et al.*, 2010) whereas the simulated volumes for these two scenarios peak at 271.92 $m^3 ha^{-1}$ for scenario 2 in 2075. Although this is lower than the expected values from Europe, it is in keeping with the actual values recorded in the Trial Area in 2008 (Mackintosh *et al.*, 2012). Scenario 2 for the 2008 scenario produced values of q and k far exceeding those found in CCF, though scenario 3 produced values that are much closer to the established guidelines (Schaeffer *et al.*, 1930; Gul *et al.*, 2005). By 2075, both scenarios produce values of q that are typical of CCF stands and close to those for the entire Glentress Trial Area, though lower than those that currently apply to C2. When implementing this CCF management, care should be taken to thin out trees competing with potential final crop trees and shading advanced regeneration. This crown thinning approach is that favoured by the current management plan for the Trial Area (Kerr *et al.*, 2010b).

Scenarios 4, 5 and 6 aim to approximate the management that has taken place between 1954 and 2008 and simulate the effect that management had on stand structure. They only differ in that underplanting takes place in scenarios 5 and 6. All three scenarios result in higher values of q and k than those produced by scenarios 2 and 3. However, scenario 5 (1954-2008) and scenario 6 (1954-2008) result in values similar to those found in C2 in 2008 and only slightly higher values of q and k than those in the rest of the Trial Area (Mackintosh *et al.*, 2011) and in another CCF trial at Faskally (Cameron and Hands, 2010). Group selection systems, providing the soils are not too fertile and the seed bed conditions are suitable, can result in prolific natural regeneration (Malcolm *et al.*, 2001). Indeed, this is the case in this part of the Trial Area at present and is likely to be a contributing factor to the high values of q and k. Prolific regeneration may necessitate respacing which has an associated economic cost (Davies and Kerr, 2011).

These simulated results show that scenarios 5 and 6 best describe the actual stand structure and are viable as a management option for continued transformation to CCF. However, the simulated results show that scenarios 2 and 3 also result in reverse-J shaped diameter distributions and result in expected values of q (1.3-1.6) by 2075. Whether the output from scenario 2, where the stand is thinned to a residual basal area of $35m^2\ ha^{-1}$ is reliable is uncertain (see section 5.4.4) but that still leaves two possible forms of management that fulfil the management goals set out for the Trial Area (Kerr *et al.*, 2010b). The reverse-J and EGS approaches make use of direct measurements from the stand and therefore yield more valuable information to the forest manager over short time periods. However, unlike patch models such as PICUS, they are incapable of incorporating the effects of climate change or simulating the long term effects of a specific management type and therefore can not be used when setting long-term management strategies or selecting suitable species in the face of climate change (Lexer and Honninger, 2001).

Based on the output from PICUS v1.4 either thinning to a low basal area (scenario 3) or a using a group selection system with the option of underplanting (scenario 6) should result in increased structural diversity as is set-out in the Glentress Trail Area management plan (Kerr *et al.* 2010b). As soil quality, and thus regeneration potential, is variable throughout the area it may be necessary to plant some areas, whilst in others respacing will be needed at some stage. Respacing should not take place until the regeneration is two to three metres high and shows differentiation, at which point the respacing should be selective (Mason, 2008). The economics of these operations should be considered as both planting and respacing are shown to result in costs in excess of those incurred by a clearfell-replant system (Davies and Kerr, 2011)

5.4.3 In situ carbon storage

Estimated *in situ* carbon storage varied both between scenarios and according to the modelling approach employed. Differences between estimation methods may be explained as PICUS v1.4 starts off using the initialisation values detailed in Table 2, where as initialisation of the WCC look-up tables are based on a cleared site. In addition the WCC thinning regime is limited to a standard thin with a 5 year cycle (West and Matthews, 2011), whereas the thinning in scenarios 2 and 3 is based on a residual basal area system on a 6 year cycle. Lastly, the WCC takes emission due to woodland management into account which is not the case in PICUS v1.4 (West and Matthews, 2011).

Comparing across the six management scenarios employed here, the most obvious result was that non-intervention resulted in the highest store of *in situ* carbon (830.82 $tCO_2\ ha^{-1}$ in 2008 and 1352.85 $tCO_2\ ha^{-1}$ in 2075) at the expense of structural diversity. An Austrian based study simulating non-intervention in stands of Norway spruce (*Picea abies* L.) , European beech (*Fagus sylvatica* L.), Scots pine (*Pinus sylvestris* L.) and English oak (*Quercus robur* L.) produced similar results using PICUS v1.4 (~1000 $tCO_2e\ ha^{-1}$) (Seidl *et al.*, 2008). Scenarios 4, 5 and 6 showed an increase in *in situ* storage, though it was unclear whether this trend would continue beyond the simulation period. The complex stand dynamics present in forests managed under CCF may necessitate the use of more complex models such as PICUS when assessing their ability to sequester carbon.

5.4.4 Improvements to the model

The simulated output from the management scenarios could prove extremely valuable as a decision making tool for CCF managers in the UK. PICUS v1.4 is especially useful when projections into the future (on scales longer than a decade) are required that may involve changes in the environment and/or silvicultural systems associated with CCF as standard yield models do not allow this (Johnsen *et al.*, 2001; Seidl *et al.*, 2005; Davies and Kerr, 2011). However, despite good correspondence between simulated output and the 2008 stand assessment, some further improvements can be made.

One potential problem occurs with the parameterisation of the regeneration submodel. The critical basal area for Sitka spruce to achieve 50 % of the growth that is achieved under full light is 30 $m^2\ ha^{-1}$ (Hale, 2004). Page *et al.* (2001) also suggested a figure of 30 $m^2\ ha^{-1}$ for successful advanced regeneration. Despite the basal area of scenario 2 being higher than 30 $m^2\ ha^{-1}$, the model continued to predict the occurrence of natural regeneration, with seedlings and saplings surviving into the canopy. This is most likely a problem with the parameterisation of the model which should be improved. Rerunning scenario 2 with either improved parameterisation or thinning to a higher residual basal area (>40m^2 ha^{-1}) would be interesting to investigate the effects of seedling and sapling mortality on stand structure.

One of the few stochastic elements of the model is the recruitment submodel (Seidl *et al.*, 2005) with seed years occurring stochastically over time (Lexer and Honninger, 2001). Therefore it is unsurprising that when the diameter distribution was compared across ten runs, the greatest spread of data values was found in the smallest diameter class (7-12cm) and the highest standard deviation is in k which is closely related to the number of trees in the smallest diameter class. It is possible that for runs beyond 2075, this uncertainty in the frequency of the smallest diameter classes will begin to propagate further into the intermediate diameter classes.

As previously discussed, the history of the management of area C2, and more generally the Trial Area has not been properly documented. Management records are incomplete and natural damage caused by pests, notably deer, disease and windthrow were not recorded. As a result it is hard to establish exactly why discrepancies between reality and simulations arise. Ideally a long-term research area with all trees spatially located, a detailed record of management and a local weather station would be established.

Currently PICUS v1.4 does not allow the modelling of competition with ground fauna and of browsing damage. However, Seidl *et al.* (2006) noted that the effects of browsing could be simulated by decreasing the germination rate of a species and thereby simulating increasing mortality. Alternatively, altering species height-growth potential could be used to simulate browsing. To implement these modifications, detailed information of browsing pressure and resulting mortality would be required for seedlings and saplings.

Unfortunately, it was only possible to parameterise PICUS v1.4 for Sitka spruce. As a result an area of the Trial Area that was predominately Sitka spruce was selected.

Whilst the results are of use to pure Sitka spruce stands that are under consideration for transformation to CCF, they are still limited for many other situations. Parameterisation of the model for the other main conifer species found in Scotland would increase its applicability significantly.

Finally, many of the parameter values employed in these runs were based on data either extracted from the literature or estimated with a significant margin of uncertainty. More solid conclusions can be obtained by including an assessment of this uncertainty in the model runs.

5.5 Conclusions

The hybrid patch model, PICUS v1.4, can provide important information regarding the choice of silvicultural systems and how they impact on stand structure. Non-intervention results in a two tiered canopy and a diameter distribution that is not reverse-J shaped. Residual basal area thinning results in a reverse-J shaped diameter distribution, with a value of q that decreases with time. However, care should be taken when interpreting the model results as currently Sitka spruce regenerates and survives at basal areas in excess of 30 m^2 ha^{-1}. The group selection system results in a reverse-J shaped diameter distribution but the value of q is affected by whether underplanting takes place during the cycle. From the results it is recommended that thinning to a residual basal area less than 30 m^2 ha^{-1} is the best management option for Sitka spruce dominated areas of the Trial Area.

Estimates of *in situ* carbon storage differ between PICUS and the WCC look-up tables however this is explainable due to differing initialisations and thinning regimes. Management that retains a proportion of the canopy, such as scenarios four, five and six, ensure that carbon storage increases with time.

There have been problems interpreting why there are discrepancies between the modelled and actual stand structure. This is due to several reasons including parameterisation and lack of detail regarding the historical anthropogenic and natural impacts on stand structure. Accurate records of environmental variables and management are essential to ensure that the model best represents reality. Providing this information is available there is great scope for the use of gap models to help inform long term management strategies.

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5.7 References

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5.8 Appendix 1 – Parameter list

Table 5.7 The parameters and functions, as well as the scale they operate on, used to parameterise PICUS v1.4 with a new species.

Growth, biometrics and allometry

Name and description	*parameter / function*	*unit / scale level*
Height potential over age	f(age)	m
Diameter-height relationship of an open-grown tree (allometric relationship)	2 parameters	m/cm
Stem biomass	f(dbh)	kg BM
Branch biomass	f(dbh)	kg BM
Foliage biomass	f(dbh)	kg BM
Coarse root biomass	f(dbh)	kg BM
Fine root biomass	f(dbh)	kg BM
Biomass expansion factor, stem biomass to stem timber volume	f(dbh, h)	m^3 kg^{-1} BM
Wood density	parameter	kg m^3
Specific leaf-area	parameter	m^2 kg^{-1}

Environmental responses

Name and description	*parameter / function*	*unit / scale level*
GDD response (GDD= growing degree days)	2 parameters (min, opt)	scalar
pH response	4 parameters (min, opt1, opt2, max)	scalar
SMI response (SMI= soil moisture index)	2 parameters (opt, max)	scalar
Nitrogen response class	class	ordinal (5)
Light tolerance class	class	ordinal (9)
height growth response to light availability (see Eq. 4, Seidl et al. 2005)	f(response)	scalar

Carbon and nitrogen cycling

Name and description	*parameter / function*	*unit / scale level*
C/N ratio foliage	parameter	unitless
C/N ratio fine roots	parameter	unitless
C/N ratio coarse roots	parameter	unitless
C/N ratio wood	parameter	unitless
Annual foliage turnover	parameter	rate yr^{-1}
Annual fine root turnover	parameter	rate yr^{-1}
Extractable fraction, foliage litter (cf. Ryan et al. 1990)	parameter	fraction
Acid-soluble fraction, foliage litter (cf. Ryan et al. 1990)	parameter	fraction
Acid-insoluble fraction, foliage litter (cf. Ryan et al. 1990)	parameter	fraction
Extractable fraction, fine root litter (cf. Ryan et al. 1990)	parameter	fraction
Acid-soluble fraction, fine root litter (cf. Ryan et al. 1990)	parameter	fraction
Acid-insoluble fraction, fine root litter (cf. Ryan et al. 1990)	parameter	fraction

Aging and mortality

Name and description	*parameter / function*	*unit / scale level*
age-related decline in productivity (see Eq. 12 in Seidl et al. 2005)	f(age)	scalar
Maximum age	parameter	yr
Stress threshold dbh increment, absolute	parameter	cm
Stress threshold dbh increment, relative to dbh growth potential	parameter	rate
Minimal duration for growth-related stress	parameter	yr
Background mortality (intrinsic)	f(age, site)	rate
Transition snags to downed woody debris	parameter	rate yr^{-1}
Transition branches to downed woody debris for snags	parameter	rate yr^{-1}

Seed production and regeneration

Currently, the regeneration module consists of four height classes (x=0-3): 0-10cm; 10-30cm; 30-80cm; 80-130cm.

Name and description	*parameter / function*	*unit / scale level*
Maximum seed number per individual	parameter	N tree^{-1}
Seed year interval	parameter	yr
Seed production (share of maximum seed number) if no seed year	parameter	fraction
Age at first seed production	parameter	yr
Germination rate	parameter	fraction
Fall velocity of seed	parameter	m sec^{-1}
Range of zoochore seed dispersal	parameter	m
Share of seeds dispersed by animals	parameter	fraction
Maximum tree height	parameter	cm
Chilling requirement for seed germination	parameter	°C
Minimum temperature for successful germination	parameter	°C
Potential height growth in height class x of the regeneration module (x=0-3)	parameter	cm yr^{-1}
Stress threshold height increment absolute	parameter	cm yr^{-1}
Stress threshold height increment relative to growth potential	parameter	fraction
Minimum duration to flag stress	parameter	yr
Mortality (share of individuals) in case of stress	parameter	fraction

Chapter 6: Overall conclusions

6.1 Summary and Conclusions

The popularity of CCF has increased since the early 1990s as a result of it being capable of meeting the multiple management objectives forest managers are now required to meet. It is therefore essential that a greater understanding of CCF management is developed. One method to achieve this is to adapt knowledge already developed in countries such as Slovenia and the Swiss Jura. These countries have practiced CCF for over a hundred years, typically in Norway spruce – Beech – Silver fir forests, and have thus accrued a vast amount of knowledge regarding management interventions and stand structural response. However, the silvicultural systems used in Continental Europe must first be adapted to the species and climate of the UK.

The primary aim of this thesis was to increase our understanding of the silviculture of CCF. This was achieved through updating the state of the stand structure at the longest running CCF trial in the UK (Kerr *et al.*, 2010a), which provided useful information regarding the effects the group selection system have had on stand structure. Stand structure was then characterised using two simple models; the ideal reverse-J and the EGS. The results of this study have shown that both of these can be used to help inform management decisions. Furthermore it has investigated the physiology of Sitka spruce seedlings under different light environments and yielded data to validate a more complex model, PICUS v1.41. This study has shown that PICUS is a powerful tool that be used to explore the effects of management and changing climate on stand structure. All of this has contributed to the growing knowledge base relating to CCF management in upland, conifer forests.

This chapter summarises the key findings from this study and also suggests some potential areas for further research.

6.2 Stand structure and species composition in the Glentress Trial Area

Monitoring of the Glentress Trial Area has been sporadic; prior to this study, the last period of monitoring was in 1990. This study has provided a much needed update to the progress of transformation from an even-aged to stand to CCF. The primary aim of the Trial Area was to transform even-aged stands of conifers to an irregular structure using a group felling system over a 60-year transformation period (Anderson, 1955). Whilst this study does not claim that transformation has been achieved throughout the Trial Area, it has shown that an irregular structure is present at smaller spatial scales than have previously been analysed.

Whilst basal area has shown little change from 1990, reaching just 25.3 $m^2 ha^{-1}$ in 2008, low basal areas are essential to provide sufficient light for natural regeneration (Page *et al.*, 2001; Hale, 2004). However there have been changes to the species composition and numbers of seedlings and saplings. Between 1990 and 2008, Sitka spruce has become the dominant species in the Trial Area, in place of Norway spruce. This has also been accompanied by a decrease in light demanding species such as Scots pine and larch and an increase in shade bearing conifer species such as Western hemlock and Western red cedar. The light requirements of the species should be of prime importance to managers considering new CCF plantings as it has a large effect on the silvicultural systems available. If light demanding species are to continue to feature in the Trial Area, basal areas will need to be kept low (around 20 $m^2 ha^{-1}$ for Scots pine (Hale, 2004)) or larger groups (> two tree heights for Scots pine (Malcolm, *et al.* 2001)) selected for felling to ensure sufficient light reaches the understory. In the Trial Area the use of the group selection system has resulted in light demanding species remaining present and has also promoted an irregular structure in the majority of stands.

Although sapling (>1.3 metres high, <7cm DBH) density has decreased between 1990 and 2008, seedling (<1.3 metres high) density has increased considerably from 159 ha^{-1} to 750 ha^{-1} with Sitka spruce making up the majority, especially at higher elevations. Maintaining sufficient numbers of seedlings and saplings is important as they are eventually recruited as small trees, and thus represent the future species composition and structural potential of your stand. The management plan for the Trial Area states targets species mixtures for each Block (Kerr *et al.*, 2010b). Therefore, wherever possible species other than Sitka spruce should be favoured when thinning and whenever planting is necessary species other than Sitka spruce should be considered. As the Trial Area has experienced a decrease in saplings despite the increase in eedlings, this indicates that there is a high rate of seedling and sapling mortality. Kerr and Mackintosh (2012) have shown that sapling survival in the Trial Area is low relative to estimates for even-aged stands (Hale and Kerr, 2009) at just 37%. As a result of incomplete management records for the Trial Area it is difficult to draw conclusions why survival is so low. However, due to the limited opportunity for control measures to be implemented deer are a likely cause.

6.3 Using reverse-J curves and the EGS to inform management

Simple models such as the ideal reverse-J and the EGS have been employed in areas of Continental Europe and can act as useful guides to management (Schutz, 2001b; Schutz, 2002b; Pommerening and Murphy, 2004). This study applied these models to the Trial Area and assesses their output. Both models have shown promise, especially the ideal reverse-J curves, and could act as a simple starting point to managers who are looking to employ silvicultural systems associated with CCF.

With the reverse-J curves, the values chosen for each of these parameters can alter the ideal reverse-J curves considerably. Therefore it is imperative that sensible values, derived from analysis of management objectives, are chosen and that the resulting thinning guidance is only applied in conjunction with knowledge of the stand.

The results from the EGS for the Trial Area shows a lower growing stock and different volume distribution to those of the Swiss Jura (Schutz, 2001a). However, the volume distribution had shifted towards those outlined by Schutz (2001b) with a decrease in percentage volume in the small diameter class and an increase in the large diameter class. However, it is entirely possible that a different volume distribution and growing stock would be better suited to the UK as we have a different climate and set of species. As the Trial Area appears to still be in state of change, further periodic assessments are required. When there is little change in the volume of the growing stock and volume distribution between assessments it will be possible to establish a suitable EGS for the Trial Area. When equilibrium is reached, this value can be used as a baseline for EGS.

In many respects, the EGS and the reverse-J curves are similar methods of informing management. The fundamental differences are that the former utilises three large diameter classes as opposed to many smaller classes (typically 5 cm) and the EGS looks at the distribution of volume rather than number of trees to the diameter classes. The lack of information on trees below 16 cm DBH in the EGS means that it does not consider regeneration. This is especially important in the UK as there are many problems with regeneration to contend with such as browsing pressure, competition and lack of good quality parent crops (Hart, 1991). In principle the EGS could include smaller diameter classes, similar to those used in reverse-J analysis, and could set a lower diameter limit of 7 cm. However, as the majority of other studies use a 16 cm lowest diameter it could cause problems when making comparisons. The EGS could be carried out using basal area rather than volume. Calculating basal area from DBH is a simple practice (Matthews and Mackie, 2006) and would avoid the problems involved with volume estimation explored in chapter 3.

6.4 Understanding the physiology of Sitka spruce seedling grown under CCF conditions

Whilst planting can ensure sufficient regeneration, natural regeneration is a desirable element to CCF if it is to be economically viable (Davies and Kerr, 2011). In order to achieve sufficient natural regeneration many factors demand consideration, one of the most important being the seedlings light requirements to develop into saplings.

ADR, the leader to lateral (branches on the first whorl) ratio of a seedling, is a useful indicator of light environment for Sitka spruce. This study supported the values reported by Grassi and Giannini (2005) and Page *et al.*(2001) that an ADR over one indicated a suitable light environment for seedling growth. ADR is easily measured and this study has shown that in Sitka spruce is can give a good indication of seedling vigour. The results of this study showed that in CCF basal area is not a good indicator of canopy openness. In the most extreme case a plot that was categorised as having a closed canopy, based on basal area, had to be recategorised as having an open canopy following the analysis of hemispherical photography. As a result, hemispherical photography should be used to classify canopy characteristics wherever possible.

The study showed a linear relationship between PAR and ETR though the range of PAR values covered was low, especially in 2010. As a result, only the linear part of the relationship was observed, with closed canopy plots showing higher levels of ETR for a given PAR. The relationship between PAR and *A* was less good, especially in the closed canopy plots where there was no obvious relationship. As a result it was not possible to develop a relationship between ETR and *A*. This was most likely partly due to a lack of controlled conditions and as a result of chlorophyll flueorescence and gas exchange measurements not being recorded simultaneously. As a result, both gas exchange and chlorophyll fluorescence are needed to properly characterise seedling physiology under field conditions. However, under controlled conditions the use of rapid light response curves in controlled light environments ensures that the seedlings experience a wider range of PAR values and experience a constant light environment prior to measurement. In a controlled light environment, Bertin *et al.* (2009) found significant differences in seedling ETR between high (100%) and low (24%) light environments. As a result, controlled experiments may prove more useful for characterising seedling response to light.

6.5 The use of hybrid patch models to develop management strategies

Simple models like the ideal reverse-J provide useful information for CCF on thinning but lack the capability of looking at the long-term effects of management decisions and, like standard yield models, lack the ability to factor in the effects of climate change (Johnsen *et al.*, 2001; Seidl *et al.*, 2005; Davies and Kerr, 2011).

The group selection with underplanting scenarios, which were closest to the actual stand management, resulted in stocking densities, basal areas and standing volumes close to those of the 2008 stand assessment. The model also resulted in a reverse-J diameter distribution consistent with the actual diameter distribution. However, there were some discrepancies between the simulated output and the stand measurements. However, like Didion *et al.* (2009) and Seidl *et al.* (2005), these differences are hard to explain as management and environmental effects on stand structure over the 1954-2008 period are incomplete.

The simulated output suggests that thinning to a residual basal area and group selection systems will result in increased structural diversity. However, if carbon sequestration is a priority a management system that retains an element of the canopy, such as the group selection scenarios explored here, may be desirable as there is a greater amount of *in situ* carbon storage associated with it. Being able to test these scenarios over long time periods can help improve knowledge regarding CCF without solely relying on long-term CCF experiments. When used in conjunction, long-term experiments are ideal as sources for parameterising and validating models. Then in turn, the models can act as tools for exploring multiple future scenarios.

6.6 Key areas of research development

In the UK, the silvicultural knowledge necessary to successfully implement CCF management is still developing. Economics, climate change and timber quality, all of which were identified as “contentious issues” in chapter one, should be focussed on to establish whether they are advantageous or disadvantageous in relation to CCF. There is evidence to suggest that economics (Davies and Kerr, 2011) and carbon sequestration (Thornley and Cannell, 2000; Seidl *et al.*, 2007; Seidl *et al.*, 2008) may have benefits and that timber quality shows no significant change (Macdonald *et al.*, 2009) relative to clearfell-replant systems. However, many of these studies are modelling exercises and therefore there is little empirical evidence of these benefits. Long term trial areas are essential to establishing the full range of advantages and disadvantages of CCF. Such areas not only provide ideal sites for research activities but also act as real-world examples of the effects different silvicultural systems have on stand structure. Within such trial areas, trees, saplings and seedlings would need to be spatially mapped and all environmental and anthropogenic impacts recorded routinely. In addition these trials could act as sources of data for parameterising and validating models of uneven aged stand development.

Further stand assessments are essential for establishing a suitable target EGS for an upland, coniferous forest in south Scotland. An ideal EGS volume distribution, unlike an ideal reverse-J distribution, cannot be generated based on stand parameters; instead it is gained from actual stand measurements. These measurements should ideally be taken from a fully transformed, CCF stand where the growing stock and volume distribution remain similar between stand assessments. Such stands are lacking in the UK and therefore periodic assessments are necessary in order to establish when transformation to CCF is complete. Only then can a suitable EGS be established

PICUS has provided realistic results for a Sitka spruce dominated area of the Glentress Trial Area. Sitka spruce accounted for 32 percent of the UKs woodland cover in 2011 (Forestry Commission, 2011). Therefore it is likely that many areas undergoing transformation to CCF will involve Sitka spruce. However, the applicability of PICUS to other woodlands could be considerably improved if it was parameterised for other UK tree species. At present the model would benefit from an improved parameterisation for Sitka spruce. Furthermore, an exploration of further scenarios both in terms of changing climate and different silvicultural prescriptions could yield useful information regarding the species choice and management.

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Appendix A

Long-term survival of saplings during the transformation to continuous cover

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Abstract

The Glentress Trial Area is an extensive research area in southern Scotland of 117 ha where a long-term trial of the transformation of even-aged plantations to continuous cover has been in progress since 1952. During the assessment of permanent sample plots in 1990 information on the species and spatial position of saplings (trees taller than 1.3 m with a diameter at breast height of <7 cm) was recorded. This provided a unique opportunity to investigate the long-term survival of saplings during the transformation process when the Trial Area was reassessed in 2009. The main finding was that 37% of saplings survived the 19-year period and the majority developed into trees (≥7 cm diameter at breast height). There was considerable variation between species, the lowest survival of saplings was European larch (*Larix decidua* Mill.) (13%) and the highest European beech (*Fagus sylvatica* L.) (55%); however differences between species were not significant. There were, however, significant differences between the six Blocks with three with high sapling survival (55% to 61%) but others much lower (27% to 32%). If this result is confirmed by other studies, covering a broader range of sites, management guidance that assumes 90% survival will need to be revised.

1. Introduction

In Great Britain recent policy has encouraged the use of “continuous cover” and “low impact” approaches to forest management in wind-firm conifer plantations [1–3]. This represents a significant change of direction for silviculture, as until recently the dominant system was patch clearfelling followed by restocking [4]. One of the advantages of restocking in patch clearfells is that it concentrates regeneration efforts so that vegetation management, fencing and the application of pesticides can be used to maximize survival and growth of the planted trees. Research and practice have shown that if trees survive until the end of the second growing season the probability of survival is high [5]. For example, in forests managed by the Forestry Commission restocked areas must have at least 2500 stems per hectare five years after planting to be considered established [6]. After this there is an assumption, justified on the basis of practice over many decades, that survival will generally be high until self-thinning commences or silvicultural operations remove trees.

The use of continuous cover changes the focus of regeneration effort. One of the main changes is that natural regeneration is often the default option [7]. This has the effect of removing the tight control associated with restocking and the forest manager must try to balance a complex set of factors in an attempt to achieve success. The main factors involved in natural regeneration can be divided into five groups: seed supply; seedbed conditions; ground flora; animal impacts and stand conditions. However, once a tree has become established there is a subtle change in the balance between these factors with the former three, which are largely related to seed and the substrate, becoming less important for survival and the latter two becoming prominent [8,9]. There is also an additional factor to consider as young trees can become damaged or killed during harvesting [10,11]. In general, the terms “seedling” and “sapling” are used to describe young trees, with seedlings being the smaller trees that are not yet established. A standard definition of a sapling is “a usually young tree larger than a seedling but smaller than a pole—note size varies by region” [12]. For example, Marquis [13] regards saplings as between 1.3 and 15 cm diameter at 1.3 m above ground level; whereas in Britain a sapling is taller than 1.3 m but also has a diameter at breast height (DBH) of <7 cm and a seedling is defined as being any tree less that 1.3 m tall [14].

In Britain the recommended method of collecting stand level data for even-aged stands being transformed to continuous cover requires the number of saplings to be counted for each species in fixed area plots [14]. The guidance also suggests adequate sapling densities and distributions at different stages of the transformation process. Data are also collected on the presence of seedlings but the logic of placing emphasis on the saplings is that there is a much higher chance of them surviving to maturity. The question of "how high is high?" has often been asked and until now there has been an assumption that 90% of saplings will develop into trees [15]. A unique opportunity arose in the Glentress Trial Area [16] to examine the long-term survival and development of saplings in an upland coniferous forest under active transformation to continuous cover. The objectives of this study were to:

1. Investigate the survival of saplings in the Glentress Trial Area between 1990 and 2009.
2. Examine the differences in sapling survival between species and Blocks.

2. Material and Methods

The Glentress Trial Area is an extensive research area of 117 ha where a long-term trial of the transformation of even-aged plantations to continuous cover has been in progress since 1952 [16]. The Trial Area is divided into six management areas (A–F) and the main species are Sitka spruce (*Picea sitchensis* (Bong.) Carr.) (43% of trees), Norway spruce (*Picea abies* (L.) Karst.) (25%), Japanese larch (*Larix kaempferi* (Lamb.) Carr.) (13%) and Douglas-fir (*Pseudotsuga menziesii* (Mirb.) Franco) (6%). The main method of transformation has been small coupe felling, with sizes in the range of 0.05 ha to 0.2 ha, followed by replanting. In the early phase of the transformation the objective was to plant Norway spruce, European silver fir (*Abies alba* L.) and European beech (*Fagus sylvatica* L.) as described by Anderson [17,18]. More recently both natural regeneration and planting have been used. However, a significant factor affecting the survival of young trees throughout the history of the Trial has been the impact of animals. Early on sheep in the area caused many problems and in later times the number of deer (roe deer; *Capreolus capreolus* L.) has increased. Deer control in the Trial Area is difficult as the area has high recreational use due to it being one of the most popular mountain biking destinations in Britain.

During its history the Trial Area has been periodically assessed in an attempt to track the structural changes that have resulted from the transformation. In the early part of its history this was done using the Check method [19] in which all trees of 12.5 cm DBH and above were assessed. However, for the assessment in 1990 a network of permanent sample plots (40 m × 10 m) were established using a stratified random design. This resulted in the establishment of 240 permanent sample plots distributed throughout six management areas (historically called "Blocks", these are described in more detail in [16]). Each of the plots was divided into four subplots that measured 10 m × 10 m. In 1990 a wide range of assessments took place on the trees, saplings, seedlings and vegetation, which are described in detail in [16]. The main focus of this study is the number of saplings, which was recorded in 1990 for each species in each subplot. In addition, a sketch plan was drawn by the assessor of each sub-plot showing the location of saplings and young trees. One assessor carried out all the work but unfortunately he did not follow a consistent approach to drawing the sketch plans, hence they vary in quality of how the spatial location of saplings was recorded. For example, in plot 12 of management area D the location of individual and groups of saplings was recorded accurately (Figure 1). In contrast, in plot 7 of management area E the data showed that saplings were present but the location of them was not recorded.

The permanent sample plots were reassessed in Autumn 2009 and this provided an opportunity to trace the development of the saplings that were recorded in 1990. During the assessment it was only possible to relocate 210 of the original 240 plots. To take account of the different ways in which the location of saplings had been recorded in 1990 five categories were defined. To ensure that these categories were defined in a repeatable, objective way during fieldwork a decision tree was designed and this is shown in Figure 2. The five categories were defined as follows:

Category 1: a tree was present in 2009 and the sketch shows its exact location as a sapling in 1990.

Category 2: a tree was present in 2009 and the sketch shows its approximate location in 1990.

Category 3: a tree was present in 2009 but the only evidence for it as a sapling in 1990 was in the data. Field checks on the age of the tree in 2009 indicate it was likely to be a sapling in 1990.

Category 4: a sapling was present in 2009 and the sketch shows its exact location as a sapling in 1990; reasons to explain the lack of development, such as browsing or stem snap, were observed.

Category 5: the exact location of a sapling was recorded in 1990 but it was not present in 2009, or a sapling is present in 2009 but there is no sign of damage to the stem and it is too small to be the original sapling present in 1990.

Figure 1. Plot sketches for subplots in management areas D and E.

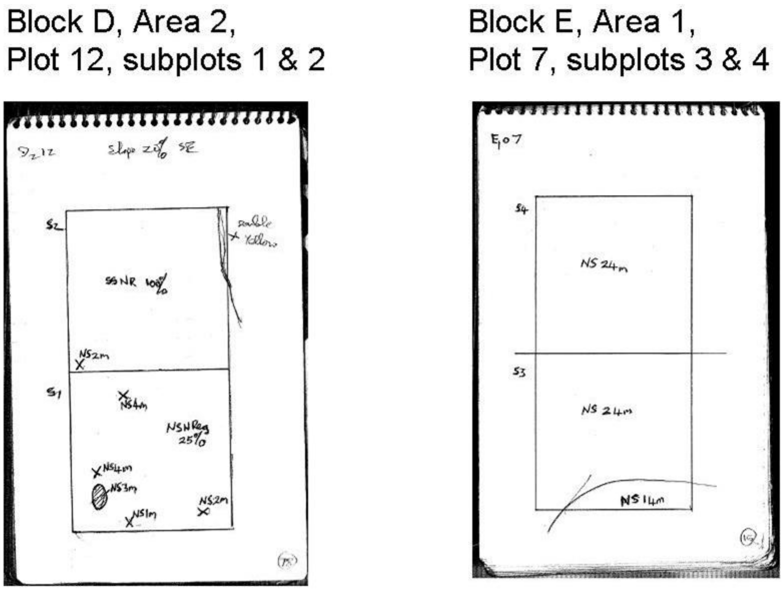
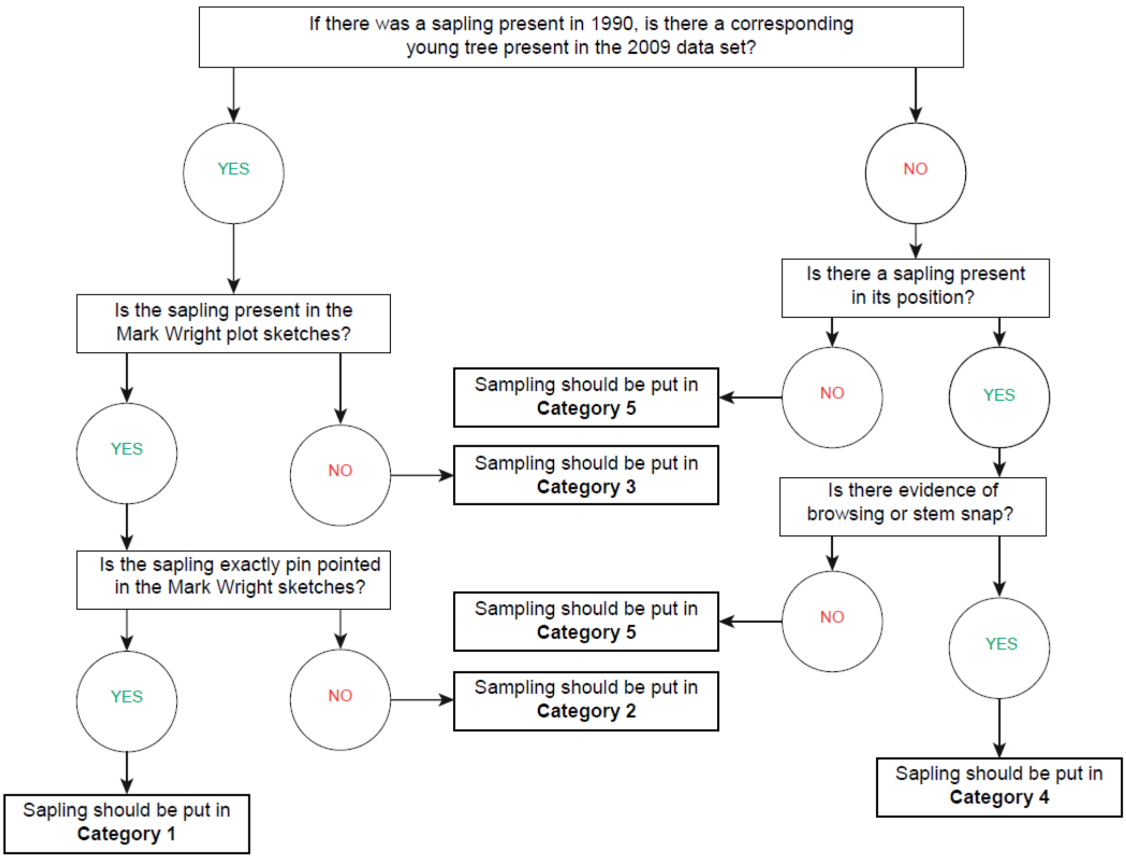


Figure 2. The decision tree used to assign saplings to categories.



The number of 1990 saplings that survived until 2009 was expressed as a percentage of those present in 1990 according to species and management area. In addition, the equivalent annual mortality proportion (*m*) was calculated for each species using the formula:

$$100/(1 + m)^{19} = Y \qquad (1)$$

where Y = the percentage of 1990 saplings that survived to 2009.

The data were analyzed using a generalized linear model (GLM) with a binomial distribution and a logit link function in version 10 of Genstat [20]. Two analyses were carried out, the first had the proportion of saplings in categories 1 to 4 as the response variable, and the second had the proportion of saplings in categories 1 and 2. In both analyses the explanatory variables were management area and species. The dispersion parameter was estimated as the data were over-dispersed.

In an attempt to interpret the results of the study in terms of existing guidance of the stocking of saplings the time taken for a sapling to develop into a tree (>7 cm DBH) was estimated. This was hampered by a dearth of data on the development of saplings under continuous cover management in Britain and therefore it was necessary to use information on the initial growth of trees in even-aged plantations. For each species a representative growth rate was assumed based on the most recent National Inventory of Woodland and Trees [21]. The yield tables of Edwards and Christie [22] were used to estimate the time taken for trees to achieve 7 cm DBH. Where the first entry in the yield table was >7 cm, a linear relationship was assumed between age and DBH, and the time to achieve 7 cm DBH was estimated by interpolation. This value is the time period it would take for a tree to achieve 7 cm DBH after planting in even-aged plantations. It was then assumed that the same time period would also apply for a sapling to achieve 7 cm DBH under CCF conditions. The effects of different initial saplings densities and annual mortalities were then investigated for these time periods.

3. Results

The 1990 assessment recorded 3155 saplings in the Trial Area and the majority (88%) of these were recorded in a defined area in the sketch plans for the assessment plots (Table 1). Only a small number (2%) had the exact location recorded and a minority (10%) had no spatial information recorded (Table 1). The main change between 1990 and 2009 was that 62.7% of the saplings could not be relocated and were assumed to have died. Most of the remaining saplings had developed into a tree but a small number (16) had not reached the point at which they could be classed as a tree, *i.e.*, 7 cm DBH.

Table 1. The number of saplings in each category in 1990 and 2009.

Category	Number in 1990 (%)	Number in 2009 (%)
1	73 (2)	28 (<1)
2	2770 (88)	1031 (33)
3	312 (10)	99 (3)
4	-	16 (<1)
5	-	1981 (63)
Totals	3155	3155

Fitted models using species and management area explained much of the variation in survival of saplings in categories 1–2 and 1–4 (both $p < 0.001$). Checks on the residual variation confirmed the adequacy of the model fitting process. Results were so similar for the analysis of saplings in Categories 1–4 and 1–2 that Tables 2–4 only show the results from the former.

Table 2. Survival of different species between 1990 and 2009 of categories 1–4.

Species	Number Present in 1990	% Alive in 2009	Equivalent Annual Mortality [*m*] (%)
European beech	31	54.8	3.2
Douglas-fir	112	34.8	5.7
European larch	45	13.3	11.2
Japanese larch	100	49.0	3.8
Lodgepole pine	104	35.6	5.6
Norway spruce	1120	37.6	5.3
Other broadleaves	20	20.0	8.8
Other conifers +	76	35.6	5.6
Sitka spruce	1318	38.2	5.2
Sycamore	72	26.4	7.3
Total	2998 *		
Trial Area		37.3	5.3

* 157 saplings classified as "mixed conifer" in the 1990 assessment were excluded from this total but not the mean % survival; + The "other conifers" group consisted of Corsican pine (*Pinus nigra* subsp. *laricio* (Poir.) Maire), Lodgepole pine (*Pinus contorta* Douglas ex Loudon), Grand fir (*Abies grandis* (Douglas ex D. Don) Lindl.), Noble fir (*Abies procera* Rehd.), European Silver fir (*Abies alba* Mill.), Western hemlock (*Tsuga heterophylla* (Raf.) Sarg.), Western red cedar (*Thuja plicata* Donn ex D. Don) and Scots pine (*Pinus sylvestris* L.). The "other broadleaves" group contained Elder (*Sambucus nigra* L.), Silver birch (*Betula pendula* Roth), Rowan (*Sorbus aucuparia* L.), Sessile Oak (*Quercus petraea* (Matt.) Lieb.) and Whitebeam (*Sorbus aria* (L.) Crantz).

Table 3. Summary of generalized linear model (GLM) analysis for categories 1–4.

Factor	DF	Deviance	Mean Deviance	Deviance Ratio	Probability (Approx. F)
Management Area	5	265.5	53.09	13.70	<0.001
Species	10	57.9	5.79	1.49	0.184
Residual	34	131.8	3.88		
Total	49	455.1	9.29		

Dispersion parameter was 3.88.

The range in the survival of different species was wide (Table 2) with the lowest being European larch (*Larix decidua* Mill.) (13.3%; annual mortality 11.2%) and the highest beech (54.8%; annual mortality 3.2%). However, the majority of saplings were Norway spruce and Sitka spruce and the survival of these species was similar, 37.6% and 38.2% respectively; close to the overall percentage survival of the Trial Area of 37.3%. The analysis confirmed that there was no significant difference between the survival of different species between 1990 and 2009 (Table 3). In addition, using the seedling light requirement classification in [23] there was little difference between light demanding species (the larches and lodgepole pine; 36.9%), intermediate (Douglas-fir and Sitka spruce; 37.9%) and the shade tolerants (Norway spruce, sycamore (*Acer pseudoplatanus* L.) and beech; 37.3%).

The survival of saplings in different management areas formed two distinct groups (Table 4). Survival was high and between 54.9% and 61.3% in management areas A, B and D but in management areas C, E and F it was much lower and in the range 26.5% to 32%. Management area C had the most saplings present in 1990 and 92% were Sitka spruce and Norway spruce. Analysis confirmed that management area had a significant effect on survival ($p < 0.001$) (Table 3).

Table 4. The number of saplings in each management area during 1990 and the percentage alive in 2009 for categories 1–4.

Management Area	Number in 1990	% Alive in 2009
A	398	55.0
B	162	54.9
C	1288	26.9
D	416	61.3
E	438	26.5
F	453	32.0
Total	3155	
Trial Area		37.1

The time taken for saplings to develop into trees was in the range of 10–17 years for conifers and 20–25 years for oak and beech (Table 5). As the Trial Area is predominantly an upland conifer forest the values of 10 years and 15 years were both used to examine the effects of different initial saplings densities and annual mortalities on the density remaining at the end of the period (Table 6). This shows that an initial density of 2000 saplings per hectare can result in between 725 and 1489 saplings depending on the time taken to achieve 7 cm DBH and the annual rate of mortality.

Table 5. Estimated time for species to achieve 7 cm diameter at breast height (DBH) under continuous cover management in Britain.

Species	General Yield Class [1]	Years to Achieve 7 cm DBH-Even-Aged [2]	Years to Achieve 7 cm DBH-CCF [3]
Douglas-fir	14	11	11
European larch	8	12	12
Japanese larch	10	10	10
Lodgepole pine	8	15	15
Norway spruce	12	17	17
Sitka spruce	14	13	13
Oak	6	20	20
European beech	6	25	25

[1] As defined by Edwards and Christie [22]; [2] From Edwards and Christie [22], assuming a linear relationship between age and DBH for the period up to the first yield table entry; [3] Estimated time from becoming a sapling to achieving 7 cm DBH; *i.e.*, assuming that the gains of starting as a sapling are equal to any reduction in growth caused by the canopy.

Table 6. Effects of different rates of annual mortality on initial densities of saplings and development into trees over 10 and 15 years.

Initial Density of Saplings per Hectare	Annual Mortality (%) *	Residual Density of Trees after 10 Years	Residual Density of Trees after 15 Years
	3	744	642
1000	5	614	481
	7	508	362
	3	1489	1284
2000	5	1228	962
	7	1016	725
	3	2233	1927
3000	5	1841	1443
	7	1525	1087

* The annual mortality proportion (m) is this figure divided by 100.

4. Discussion

Knowledge and understanding of the development and mortality of saplings is important when using continuous cover management as they have a profound effect on the dynamics and future composition of the forest, particularly where there is more than one species [24,25]. When transforming even-aged stands to continuous cover management two quite different scenarios operate. In the first, something akin to a uniform shelterwood [26], dense uniform seedling regeneration is established and then the overstorey is removed in a single or series of operations. A good example of guidance for forest managers on the density and species composition of saplings for this scenario has been developed by Marquis [13]. This gives guidance on the relationship between the size and species composition of seedling and sapling regeneration, deer density and food availability, and the likelihood of successful regeneration; it was based on a number of studies [27,28]. In the second, a slower more gradual process of regeneration will result in a forest with a structure similar to that produced by an irregular shelterwood or selection system [26]; this is the aim at Glentress [16].

In fully developed selection systems, forest managers seek to ensure certain levels of "ingrowth", which is defined as a number of trees or basal area that develops to a minimum size within a set period of time [29]. The criterion at which trees are classed as ingrowth can be as low as a DBH of 5.5 cm [30] or as high as a DBH of 16 cm [31–33]. However, in terms of guidance to forest managers, one problem with this approach is that it gives no information on the earlier stages from seedling to sapling and from a sapling to tree. This is particularly important when transforming even-aged stands to an irregular structure when mammal impacts can be significant, such as in Britain. A recent survey to find guidance in a range of different countries on the number of saplings considered to be sufficient did not locate much relevant information that could be used to inform practice in Britain [15]. However, a number of studies of sapling development and mortality have been published [8,34–37] and it is clear from these that the survival of a sapling is related to its size and rate of growth, the shade tolerance of the species, site and the impacts of mammals. Models of sapling growth have also been developed [38,39] but an important concern with any regeneration model is availability of data [40].

Present guidance in Britain [14,41] is that when transforming to continuous cover and the production of timber is an objective of management a density of 2000 saplings per hectare with an even distribution is required. When using the uniform shelterwood system this density should be achieved 10–15 years after the seeding felling. When using an irregular shelterwood or selection system this density should be achieved on 10% of the area after 10–15 years, with the area increasing thereafter depending on the nature of the site and species being managed. These figures were derived based on the assumption that 90% of the saplings would survive [15]. The main finding of this study is that this assumption is ambitious at least for some sites as at Glentress only 37% of saplings developed into trees during the 19-year period of the study.

The range of survival between different species was wide (34.8%) but was not significant. However, it should be noted that the lowest and highest surviving species had lower sample sizes than the majority of the tree species. Neither were there any differences apparent between groups of species of different shade tolerance. The effect of management area across the Trial Area was found to have a significant influence on sapling survival. There are a large number of factors that could explain this effect but unfortunately with the dearth of historical records available for the area it is impossible to explain these results [16]. However, the results can be considered in the context of guidance that a minimum density of 2000 saplings per hectare is required during transformation to CCF [14]. The mean annual mortality of the species was 5.3% (Table 2) and if this rate of mortality is applied over a 10 or 15 year transformation period then the resulting sapling densities will be 1228 per hectare or 962 per hectare respectively (Table 6). This prompts the question: "is this density sufficient to ensure the production of quality timber?" [42]. As shown in Table 6 the effects of longer transformation periods and higher annual mortalities are to reduce this figure much further.

Only a small number of other studies have been located that present results from similar sapling developmental stages. A notable exception to this is the study of Kobe and Coates [34] who examined the influence of growth and shade tolerance of the saplings of eight tree species in northwestern British Columbia. Their results show that for saplings growing well (4 mm annual diameter increment at 10 cm above ground) the three year probability of mortality varied between 0% and 4%. However, for saplings growing poorly (1 mm annual diameter increment) the three-year probability of mortality varied between 0% and 70%. These results show a wider variation than the present study but little information is given on the possible effects of mammal impacts or harvesting damage, both of which could have been important at Glentress.

The information above suggests that guidance on the minimum density of saplings may need to be revised. However, it should be noted that these results come from only one site and variation between sites would be expected to be high. However, the site covered a large area and in many respects is a typical upland coniferous forest. The main ways in which it is different to surrounding forest areas is the high level of public access for mountain biking and the problems this causes for deer control. The Trial Area is consequently likely to have higher mortality rates of saplings compared with other areas. Perhaps the best way forward is for forest managers to apply the monitoring procedure described by Kerr *et al*. [14] and develop guidelines based on local factors.

5. Conclusions

1. A large number of factors contribute to the mortality of a sapling. This study has shown that previous assumptions in Britain of high survival rates were not confirmed at the Glentress Trial Area. If this is confirmed by data from a broader range of sites, present guidance to forest managers may need to be revised.
2. The location of a sapling can have a significant effect on the survival of a sapling. More work is required to better understand the complex factors that have produced this result.
3. Information on the link between stocking densities of saplings and a range of objectives of forest management, particularly timber production, is lacking in the context of continuous cover management. Because of this any future revised guidance should take account of the precautionary principle—if you are aiming to produce timber it is much better to have more saplings as these can always be thinned to produce the species composition and spatial arrangement required.

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7. References

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